

CALIFORNIA  
ENERGY  
COMMISSION

**2004 Annual Review of the PIER Program  
Volume 5 – Environmentally-Preferred  
Advanced Generation  
Project Summaries**

**STAFF REPORT**

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## **EPAG Multi-Year Projects Started in 2004**

## **Development of a Cost Effective NO<sub>x</sub> Reduction Retrofit for Stationary Diesel Engines**

**Contract #:** 500-02-014 **Work Authorization #:** E2I-WA-118

**Contractor:** Catalytica Energy Systems, Inc.

**Subcontractors:** Catalytica Energy Systems, Inc.

**Project Amount:** \$507,000

**Match Amount:** \$117,000

**Contractor Project Manager:** Suresh Vilayanur (650) 940-6229

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

Several utilities approached the Electrical Power Research Institute (EPRI) to study the possibility of using the utilities' customer backup generators (BUGs) for peak power demand response/reduction. However, the utilities cannot dispatch those units because of emission constraints. Sustained operation would require nitrogen oxides (NO<sub>x</sub>) reductions of more than 90%, and the only technology that can accomplish this is selective catalytic reduction (SCR), which is too expensive for small diesel engines.

Another application for clean stationary diesel engines is to drive agricultural water pumps. Because of significant air quality degradation in the Central Valley of California from many such pumps, there is mounting political pressure to power the pumps with grid electricity. But this could push electricity demand beyond supply during hot summer months. An economical diesel NO<sub>x</sub> reduction retrofit would provide a new option.

Catalytica Energy Systems, Inc. (CESI) proposed the development of a technology that combines a throttle valve system, a fuel processor in-line with the exhaust, a NO<sub>x</sub> trap or NO<sub>x</sub> absorber from a third party supplier, and a controller that monitors engine rotations per minute (rpm) and load data to control the other components and achieve the required level of NO<sub>x</sub> control. CESI plans to include a compatible PM trap for systems operating in California.

This Work Authorization supports Phase I of this project, the design and manufacturing of the NO<sub>x</sub> reduction system (XEC90), and 100 hours of operations on CESI's 8.3-liter (160 kW) diesel genset. The goal is to achieve 90% NO<sub>x</sub> reduction. Plans for Phase II are to install the XEC90 system on end-user engines and reduce NO<sub>x</sub> by at least 95%. Phase III has a goal of 99% NO<sub>x</sub> reduction on several commonly used stationary diesel engines up to 1 MW.

### **This project supports the PIER Program objectives of:**

- Improving the energy cost/value of California's electricity by increasing the productivity of installed power generation units.
- Improving the environment, public health and safety of California's electricity by reducing NO<sub>x</sub> emissions from the power generating sources.

### **Proposed Outcomes:**

1. Fabricate, install and operate an XEC90 prototype system on a 160 kilowatt (kW) diesel engine at CESI's Mountain View R&D facility.
2. Demonstrate 100 operating hours with at least 90% NO<sub>x</sub> reduction and measure the associated fuel penalty.



**Project Status:**

The prototype XEC90 was designed, manufactured and installed on CESI's test engine and the 100-hour test was underway during December 2004. Preliminary estimates indicate NO<sub>x</sub> reductions slightly greater than 90%. The tests are to be completed in January 2005.

## Engine CHP Integrated Cooling and Heating Module Development

**Contract #:** 500-03-038

**Contractor:** D. E. Solutions

**Subcontractors:** Integrated CHP Systems, Corp. : BluePoint Energy, Inc.

**Contract Amount:** \$1,173,536

**Match Amount:** \$834,041

**Contractor Project Manager:** Keith Davidson (858) 832-1242

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### Project Description:

Current combined heat and power (CHP) systems involve the custom integration of disparate pieces (prime mover, generator, controls, heat recovery (HR), and cooling). This practice drives up engineering, equipment, and construction costs oftentimes ruining CHP economics particularly in small and medium-sized applications (i.e., 200 – 800 kilowatts (kW)).

Absorption cooling has a reputation for poor reliability and maintainability and is not configured for effective utilization of engine heat. Two overseas manufacturers have recently introduced absorption products suitable for reciprocating engine heat quality, but the technology has not been proven in the field nor has it been integrated in a cost-effective package.

The product to be developed will be an 80 ton absorption-based heating and cooling system interfaced with BluePoint Energy's 260 kW ultra-low emission reciprocating engine system.

The goal of this project is to significantly reduce the installed cost of CHP integrated heating, ventilation and air conditioning (HVAC) systems for commercial and light industrial applications. The goals will be accomplished through: 1) the development of standardized factory assembled heating/cooling modules, and 2) absorption chiller and engine heat management system that are cost optimized for CHP performance.

### This project supports the PIER Program objectives of:

- Improving the energy cost/value of California's electricity by developing and demonstrating and thus improving the economics of CHP as applied to HVAC systems in the commercial and light industrial sectors.
- Improving the reliability, quality, and sufficiency of California's electricity by enabling widespread implementation of CHP in California's commercial and light industrial sectors, which relieves pressure for new central station capacity and transmission lines, and increases power quality/reliability for the CHP adopters.

### Proposed Outcomes:

1. Increase engine heat recovery (HR) outlet temperature to 215°F.
2. Reduce HVAC system and interface costs by 35%.
3. Increase the CHP economically-addressable market in the commercial and light industrial sectors by threefold.
4. Reduce the cost of electricity to targeted commercial and light industrial customers by 25%.

### Project Status:

The project is on schedule and within budget. It is expected to be completed by December 2007.

## **Field Demonstration of Catalytic Combustion System for Non-Ammonia Control of Gas Turbine NO<sub>x</sub> Emissions**

**Contract #:** 500-01-025 **Work Authorization #:** E2I-WA-010

**Contractor:** Electricity Innovation Institute

**Subcontractors:** City of Riverside, California

**Project Amount:** \$312,342

**Contractor Project Manager:** David Thimsen (650) 855-2548

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

Siting of small gas turbines in distributed power applications has been limited due to the cost of meeting nitrogen oxides (NO<sub>x</sub>) emission regulations. Costly selective catalytic reduction (SCR) technology is required to achieve NO<sub>x</sub> levels under 5 parts per million. Catalytica Energy Systems, Inc.'s Xonon® combustion technology was developed as a cost effective solution to mitigate high NO<sub>x</sub> emissions from gas turbines and is commercially available for small 1.4 megawatt (MW) gas turbines. In collaboration with General Electric–Aero Energy Products (GE-AEP), a retrofit combustor has now been developed for larger 10 MW class turbines.

This project will provide funds to the City of Riverside to retrofit one of four existing GE-10 gas turbines (11 megawatt electric (MWe)) owned by Riverside Public Utilities (RPU) with a Xonon® combustor. An existing high SCR will be decommissioned. The goal of the project is to control NO<sub>x</sub> to less than 2 parts per million by volume (15% oxygen) during an accelerated 4,000-hour field test in order to accelerate commercial deployment and broader availability of this technology in marketplace. The project will record and report on operating performance of the retrofitted engine compared side-by-side with identical engines using SCR. The data will include heat rate, power output, NO<sub>x</sub> emissions, variable operations and maintenance cost, and operational flexibility.

This project will demonstrate the commercial readiness of the Xonon technology at the 11 MW scale for an industrial size turbine in a utility peaker plant setting. Successful completion will provide the power generation industry with critical operating data from an end-user application of Xonon, and accelerate the deployment of catalytic combustion to meet stringent gas turbine emissions requirements without exhaust clean-up. This will benefit the nation by enabling distributed generation deployment while maintaining public health and safety. The cost of NO<sub>x</sub> mitigation will be significantly reduced, especially on smaller scale gas turbines. End-users will gain operational flexibility – the opportunity to qualify as spinning reserves – because start-up will not be delayed by SCR purge and warm-up operations. At sites where Xonon is deployed, the cost and hazard of transporting and storing ammonia will be eliminated, as will ammonia slip into the air.

The California Energy Commission, the U.S. Department of Energy, the City of Riverside, Alliance Power, GE-AEP, Catalytica, and Black & Veatch are collaborating with Electrical Power Research Institute's (EPRI) Distributed Resources Program and specific EPRI members on this project. It will also be supported by an E2I Work Authorization through Contract #500-02-014 to analyze data generated by the project, organize a Utility Advisory Committee comprising contributing EPRI members, and engage in technology transfer of information about the project to all EPRI members.

**This project supports the PIER Program objectives of:**

- Improving the environment, public health and safety; and providing greater choices for California consumers by supporting the demonstration of a very low NO<sub>x</sub> power generation technology that will meet the stringent California standards without the use of toxic chemicals and exhaust clean-up systems, thereby providing a technology choice for Californians that meets the environmental requirements.

**Proposed Outcome:**

1. Accelerate the commercial introduction of very low NO<sub>x</sub> emission gas turbines in the 10 MW range, without the use of exhaust clean-up systems.

**Project Status:**

Catalytica has manufactured two Xonon modules and shipped them to GE-AEP's GE-10 test facility in Italy. Upon completion of the tests early in 2005, GE will decide whether or not to proceed with the project. No funds will be released until full project funding is secured and GE-AEP commits as a project participant and signs an agreement with the City of Riverside to provide a Xonon-equipped GE-10 gas turbine to RPU.

## High Efficiency Ultra-Low NO<sub>x</sub> Supplemental Firing Burner

**Contract #:** 500-03-040

**Contractor:** Alzeta Corporation

**Contract Amount:** \$1,521,321

**Match Amount:** \$561,784

**Contractor Project Manager:** John Sullivan (408) 727-8282

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### Project Description:

The purpose of this project is to demonstrate a new type of supplemental firing burner for combined heat and power (CHP) applications. The new burner will provide a system efficiency that approaches that of standard industrial boilers, while also matching the nitrogen oxides (NO<sub>x</sub>) and carbon monoxide (CO) emissions currently considered to be the best available control technology for boilers in California.

In a common system configuration, supplemental firing is the addition of heat by means of a burner to the exhaust gas from a gas turbine or a reciprocating engine before the exhaust gas enters a heat recovery steam generator (HRSG). Using a supplemental firing or duct burner can improve a CHP system. It can improve operating flexibility, provide higher thermal efficiency, and increase the steam-to-power ratio. However, adding a duct burner to a CHP system can also require costly stack treatment to meet emission limits. The project will develop a duct burner that meets emissions limits without stack treatment.

### This project supports the PIER Program objective of:

- Improving the reliability, quality, and sufficiency of California's electricity by significantly improving the cost effectiveness of the cogeneration of electricity and steam at industrial and large commercial institutional facilities.

### Proposed Outcomes:

1. Introduction of a new supplemental firing burner design that increases the overall thermal efficiency of gas turbine combined heat and power systems to 80% based on fuel higher heating value when recovering waste heat as 150 pounds per square inch gauge (psig) steam.
2. Achieve sub-9 parts per million (ppm) NO<sub>x</sub> emissions and sub-50 ppm CO emissions, corrected to 3% stack oxygen, from the supplemental firing burner.
3. Demonstrate the supplemental firing burner design in an industrial application with a 1-5 megawatt electric (MWe) gas turbine (or similar power generating device), and with a significant demand for process heat.

### Project Status:

The project is on schedule and within budget. It is expected to be completed by December 2006. Three prototype burners have been fabricated and are undergoing testing.

## **Power Generation Integrated in Burners for Packaged Industrial/Commercial Boilers**

**Contract #:** 500-03-037

**Contractor:** CMC-Engineering

**Subcontractors:** Lawrence Berkeley National Laboratory : COEN Company, Inc.

**Contract Amount:** \$1,505,827

**Match Amount:** \$381,443

**Contractor Project Manager:** Carlo Castaldini (408) 314-0382

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### **Project Description**

Commercial combined heat and power (CHP) systems are grouped by size into large industrial (>25 megawatt electric (MWe)), small industrial (50 kilowatt electric (kWe) to 25 MWe) and small commercial/institutional (25 to 250 kWe). Large and small industrial systems in the MWe range are typically more efficient, benefit from economies of scale, and are installed in industries that are well experienced and adapt to their operations. Contrary to these large systems, which are well accepted by industries, smaller commercial/institutional CHPs, are not readily embraced by potential users. Small reciprocating engine or microturbine generator (MTG) in the 25 to 250 kWe range for commercial/institutional CHP applications are offered today either in packaged systems with heat recovery for hot water (i.e., Capstone and Bowman) or as stand alone prime movers that can be combined with thermal energy equipment such as chillers or boilers. Some vendors (e.g., Capstone, United Technologies Corporation, Honeywell, Solar Turbines, Ingersoll-Rand, Dresser, and Ni-Source) mislabel these prime mover-thermal units assemblies as “packaged-CHP” where instead they are simply modular, combining individual components in a CHP arrangement. The overall CHP efficiency of the packaged hot-water CHP systems is limited to a range of 60 to 70 percent because of the sensible heat remaining in the flue gas. Though CHP systems with fired heat recovery can reach higher efficiencies as a result of the reburning process – as is often the case in the larger industrial size units – the primary deficiencies that hinder widespread applications of these smaller units remain, principally: (1) lack of a single truly packaged commercial configuration and of a “one-stop shop vendor,” (2) higher capital cost of prime mover (up to \$1,500/kWe installed), and (3) sufficient reliability and low maintenance.

This project addresses these deficiencies by focusing on the development of a truly packaged CHP assembly that combines the benefits of a simple MTG??? configuration integrated with a burner/windbox assembly that offers the compactness of current burner systems with the added benefit of distributed generation (DG). The capital cost of the MTG will be reduced by removing high-maintenance components, such as the recuperator, and embedding the core equipment inside a windbox assembly. A similar, but less flexible, concept was introduced by Bowman Power in Europe and funded by the European Union community. That concept, however, is not sufficiently flexible for the broader market of potential CHP users in small industrial/commercial and institutional applications because it does not allow for flexibility in the kWe versus thermal load capacities. In that system, the thermal unit capacity is limited by the available airflow of the MTG. The packaged CHP configuration of this project will offer measurable advantages over current baseline systems.

The proposed project improves on the cost of electricity generation by introducing CHP efficiency to many existing industrial/commercial boilers currently not availing themselves of efficient power generation. Improvement over conventional CHP-based electricity generation will be based on boosting overall CHP efficiency an incremental 5% above conventional CHP

systems. Reducing the investment cost compared to modular-CHP systems and reducing the retail cost of the MTG component will accomplish the reduction in cost of power generation. Existing packaged burner systems will have the option of integrated CHP. The existing population of packaged single-burner boilers will have a new retrofit burner assembly that will include DG capability, fully integrated in a streamline package. This will significantly enhance the acceptance of CHP by the steam generation industry.

**This project supports the PIER Program objectives of:**

- Improving the energy cost/value of California's electricity by developing, demonstrating and introducing to the industrial commercial steam market a novel packaged CHP system that avails itself on existing thermal loads and provides a low-cost, clean, and efficient approach to DG.
- Improving the reliability, quality and sufficiency of California's electricity by adding a simple, integrated, reliable, and low-maintenance MTG-based power generator that will make thermal equipment more self-reliant toward auxiliary power and more efficient in generating electricity for the grid.

**Proposed Outcomes:**

1. Develop, demonstrate, and commercialize a new industrial burner/windbox assembly that incorporates a low-cost MTG for clean and efficient CHP capability. The design will pattern existing burner/windbox assembly, marketed by Coen, to minimize space requirements and promote acceptance in retrofit and new applications.
2. Reduce the cost of electricity generation by 5% compared to conventional high-quality CHP systems.
3. Reduce the cost of generation supply by 30%.
4. Increase the number of new technologies that are market-ready.

**Project Status:**

The project is on schedule and within budget. It is expected to be completed by September 2007.

## **Premium Power for Small CHP Systems**

**Contract #:** 500-03-039

**Contractor:** Tecogen, Inc.

**Subcontractors:** DE Solutions : Youtility, Inc.

**Contract Amount:** \$941,199

**Match Amount:** \$627,959

**Contractor Project Manager:** Robert Panora (781) 466-6401

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### **Project Description:**

The purpose of this project is to incorporate inverter-based technology into the Contractor's combined heat and power (CHP) engine system. The CHP system is based on a 75 kilowatt (kW) rich burn engine with a three-way catalyst. Implementation of small CHP engine packages has been shallow relative to the market potential mainly because of the induction-based technology. Induction systems are generally not capable of black start, have little grid-isolated capability, and often need capacitors to prevent power factor degradation. The evolution of California's Rule 21, driven by concerns over anti-islanding ground fault protection, is making it increasingly difficult and costly for induction or synchronous generators to grid connect. Custom-designed CHP systems have high soft costs for engineering, permitting and utility interface, and high hard costs for grid interconnection and retrofit installation.

Applying inverter-based technology to a contractor's CHP engine package removes these current limitations and market barriers. Firstly, California's Rule 21 favors inverter-based generating systems, facilitating their acceptance for interconnection to the utility grid. Secondly, black start capability fulfills an end-user demand. Thirdly, peaking capability resulting from variable speed over-speed operation capability will foster wider acceptance of distributed generation (DG) by utilities by providing demand response capability. Lastly, the option to integrate photovoltaic technology will bridge engine technology with renewable energy sources, fostering the market penetration of both technologies.

### **This project supports the PIER Program objective of:**

- Improving the energy/cost value of California's electricity by providing an enhanced combined heat and power product to the California market at a reduced capital cost and higher part-load efficiency.

### **Proposed Outcomes:**

1. Improve the Tecogen's engine-powered combined heat and power system by incorporating inverter based technology.
2. Decrease the installed capital cost by 20%.
3. Provide power independent of the grid, which means that power would be provided even during a blackout.
4. Provide peaking capacity equal to 25% of base-load power rating.
5. Add the ability to integrate the system with photovoltaic systems.

### **Project Status:**

Project is on schedule and within budget. It is expected to be complete by December 2007. The Contractor is currently testing the power generation module, which is the inverter along with the variable speed generator. The next step will be to incorporate the power generation module into Contractor's CHP system and conduct in-house testing on it.



## **Test and Evaluation of a 10 kW Solid Oxide Fuel Cell System**

**Contract #:** 500-02-014 **Work Authorization #:** E2I-WA-117

**Contractor:** Electricity Innovation Institute

**Subcontractors:** First Energy

**Project Amount:** \$53,000

**Contractor Project Manager:** David Thimsen (650) 855-2548

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### **Project Description:**

This project will assess the performance and durability of emerging solid oxide fuel cell (SOFC) systems by performing a field test and validation of a 10 kilowatt (kW) Acumentrics Corporation fuel cell system during two years of operation. This project will document the lessons learned in acquisition, siting, start-up and operation of the fuel cell system.

### **This project supports the PIER Program objectives of:**

- Improving the environment, public health, and safety of California's electricity; and of improving the reliability, quality, and sufficiency of California's electricity by testing an emerging technology that promises both efficiency and low emissions in a system that is suitable for distributed generation.

### **Proposed Outcome:**

1. This project will provide field test data in a standardized format of an emerging fuel cell product that is new to the commercial market. It is anticipated that those who may be interested in purchasing this type of technology may look at this test data to determine feasibility or installation insight.

### **Project Status:**

The site chosen for the field testing was the Cuyahoga Valley National Park in Ohio. The fuel cell has been ordered.

## **EPAG Active Projects from Previous Years**

## **A 500 kW Zero-Emission Gas-Fired Power Plant**

**Contract #:** 500-01-013

**Contractor:** Clean Energy Systems, Inc.

**Subcontractors:** Mirant Delta : Air Liquide

**Contract Amount:** \$4,003,286

**Match Amount:** \$8,599,447

**Contractor Project Manager:** Ronald Bischoff (916) 379-9143

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

The purpose of this project is to demonstrate the long-term reliability and durability of a unique fossil-fueled zero-emission power generation system based on rocket engine designs. The enabling technology is a combustor called a gas generator that produces high-temperature, high-pressure gas composed almost entirely of steam and carbon dioxide (CO<sub>2</sub>). Oxygen is used to combust the fuel, rather than air as in conventional systems, thereby eliminating the formation of nitrogen oxides (NO<sub>x</sub>) and the large volume of non-condensable exhaust gas. The high-energy gases drive a steam turbine that, in turn, drives a conventional electrical generator. For this demonstration project, a 20 megawatt (MW) (thermal) gas generator, developed and tested with Department of Energy (DOE) funding, will be operated for two years to produce electricity on the grid at a repowered 5 MW power plant near Bakersfield, California.

A demonstration of this type is essential before utilities will be willing to risk using a new technology. The CES technology is unique and innovative, and could be a revolutionary power generation breakthrough. Public benefits from use of Clean Energy Systems' (CES) technology at power plants could be substantial. Air emissions would be negligible. Exhaust from the gas generator is water, most of which is recycled, and nearly pure CO<sub>2</sub>, which can be sequestered or used commercially, e.g., for enhanced oil recovery from existing oil fields. If CO<sub>2</sub> sequestration becomes required or a carbon tax is imposed, a CES power plant would be considerably more efficient than a modern gas-fired combined cycle power plant.

### **This project supports the PIER Program objective of:**

- Improving the environment, public health and safety by accelerating the development of fossil fuel electricity generation system with nearly zero emissions and the option of CO<sub>2</sub> sequestration.

### **Proposed Outcomes:**

1. One year of non-stop operation and electricity generation with the CES system to demonstrate long term reliability.
2. A second year of operations and electricity generation under various off-design conditions to characterize the performance of the system, demonstrate durability and establish acceptable operating limits.

### **Project Status:**

In a parallel DOE-funded project, CES built and successfully demonstrated a unique 20 MW combustor for short term tests. As part of the PIER project, CES completed the design and construction of a variable rate control system to control the flow of oxygen, natural gas and water to the combustor. CES bought the mothballed Kimberlina power plant near Bakersfield, California, and is repowering the plant to use the existing 5 MW turbo-generator and interconnection equipment. Retrofitting the power plant progressed rapidly during 2004 and CES

expects to generate grid power early in 2005. The anticipated demonstration at a 5 MW power level has interested electricity generators in California and abroad. The location will also will allow for future demonstrations of CO<sub>2</sub> sequestration in a deep aquifer, or using CO<sub>2</sub> for enhanced oil recovery in nearby oil fields.

## A Proposal for an Ultra-Low Emissions System Development Project

**Contract #:** 500-02-002

**Contractor:** Waukesha Engine, Dresser, Inc.

**Subcontractors:** Miratech Corporation : Southwest Research Institute : Southern California Gas Company : Manufacturing Resources, Inc.

**Contract Amount:** \$2,995,060

**Match Amount:** \$1,570,410

**Contractor Project Manager:** David Watson (262) 650-5762

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### Project Description:

The purpose of this project is to develop and demonstrate a natural gas fueled, reciprocating engine system with emissions reduction technology and fuel reformation that meets the 2007 Environmentally Preferred Advanced Generation (EPAG) unit's advanced reciprocating internal combustion engines (ARICE) emissions-and-installed cost targets improving efficiency by 20 percent. The developed engine system will provide electrical system reliability, air emission, and economic benefits to the California ratepayers.

The goals of this project are to introduce a new engine emission control technology that will:

- Decrease engine emissions by 90 percent.
- Increase rich burn engine efficiency by 20 percent.
- Reduce installed cost of DG systems by 20 percent.
- Maintain engine durability at current levels.

This project seeks to capture the high efficiency and extremely low emissions of a lean burn engine equipped with expensive selective catalytic reduction (SCR) after-treatment, while maintaining the excellent cost benefit ratios of rich burn engines using low-cost readily available three-way catalysts.

The proposed technology improvements focus on nitrogen oxides (NO<sub>x</sub>) and carbon monoxide (CO) emissions, engine efficiency and cooling, combined heat and power (CHP) efficiency, cost and engine durability. While there will be no specific work on generator system improvements, a net increase in fuel-to-electric efficiency will be realized reflecting the engine efficiency improvements. No adverse affects are expected on volatile organic compounds (VOCs) or particulate emissions.

EPAG targets will be directly addressed by the technology development. By the end of the project in 2005, engine emissions of NO<sub>x</sub> and CO will be lowered by the combination of exhaust gas recirculation (EGR) and fuel enhancement, and a three-way catalyst will further reduce the NO<sub>x</sub> and CO to meet the 2007 EPAG targets. In addition to the positive affect on emissions, EGR and fuel enhancement technology will extend the power available from the rich burn engine by 25%, increasing its efficiency by 20% and achieving 95% of the 2005 efficiency target. Installed costs will be lowered through increased engine power and the use of a three-way catalyst instead of a more complex and expensive SCR system. The resulting cost will also come in below the 2007 target.

**This project supports the PIER Program objectives of:**

- Improving the environmental and public health costs/risk of California's electricity by attaining 2007 emissions targets in 2005. Further improvements in air quality will be achievable by retrofitting the developed technology on rich burn engines already in operation.
- Improving the energy cost/value of California's electricity by raising engine efficiency while lowering installation costs. This will reduce non-renewable energy consumption and total emissions tonnage while lowering the cost of electricity to customers.

**Proposed Outcomes:**

1. Eliminate \$1000/kW (kilowatt) cost of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on reciprocating engines.
2. Provide superior NO<sub>x</sub> performance at costs far below the cost of SCR and other alternate NO<sub>x</sub> control technologies.
3. Provide higher efficiency than other distributed generation (DG) technologies.

**Project Status:**

This project had been on schedule and within budget. However, the project is on hold due to the contract negotiations for budget and technology changes requested by the contractor.

**Advanced Laser Ignition System Integrated ARICE Project (A Consortium of CEC's ARICE and USDOE's ARES Programs)**

**Contract #:** 500-02-022

**Contractor:** Argonne National Laboratory

**Subcontractors:** Southwest Research Institute

**Contract Amount:** \$1,000,000

**Match Amount:** \$2,175,000

**Contractor Project Manager:** Sreenath Gupta (630) 252-6089

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

**Project Description:**

The purpose this project is to develop an ignition system based on the laser based ignition (LBI) concept for use in natural gas engines. Initially various design parameters will be determined through experimental studies. Such information will be used subsequently to develop the components required for an Advanced Laser Ignition System (ALIS). Finally, an integrated ALIS-ARICE natural gas engine will be tested to evaluate the performance benefits for California consumers. Subsequently, production and commercialization plans will be formalized.

In present natural gas engines used for distributed generation, lean operation to reduce nitrogen oxides (NO<sub>x</sub>) emissions along with the requirement to maintain high specific powers results in in-cylinder conditions that demand a performance beyond the capabilities of present ignition systems. Unable to overcome such limitations, these engines are operated presently well below their full potential (about 20% less). Additionally, undue maintenance demands are placed for the upkeep of these ignition systems.

LBI is a very promising technology that overcomes the above limitations and potentially reduces emissions and increases engine efficiency. Such benefits can result in improved air quality, lower electricity cost and improved grid reliability in California.

To leverage the expertise that has already been established regarding laser ignition, the proposed effort is being pursued under a consortium of various research agencies: (1) Argonne National Laboratory, (2) National Energy Technology Laboratory, (3) Southwest Research Institute, (4) Colorado State University, (5) Waukesha Engine, (6) Caterpillar Inc., and (7) Cummins Inc. Additional funding for this effort is provided by US-Department of Energy in addition to a cost-share by consortium members.

**This project supports the PIER Program objectives of:**

- Improving the environmental and public health costs/risk of California's electricity by attaining 2007 emissions targets in 2005.
- Improving the energy cost/value of California's electricity by raising engine efficiency while lowering installation costs. This will reduce non-renewable energy consumption and total emissions tonnage while lowering the cost of electricity to customers.

**Proposed Outcomes:**

1. Reduce emissions leading to improved air quality and environment.
2. Improve efficiency and enhanced power which results in conservation of energy resources.
3. Improve durability and reliability of the reciprocating engine technology for distributed generation and other stationary power applications.
4. Reduce cost of electricity.

**Project Status:**

This project is on schedule and within budget. The project is expected to be complete by July 2006.



## **An Integrated Distributed Power System Using a PEM Fuel Cell and an Autothermal Cyclic Reformer**

**Contract #:** 500-01-022

**Contractor:** GE Global Research

**Subcontractors:** National Fuel Cell Research Center

**Contract Amount:** \$1,959,013

**Match Amount:** \$2,040,987

**Contractor Project Manager:** Ravi Kumar (949) 859-8851

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### **Project Description:**

The purpose of this project is to develop a pre-commercial prototype for an Autothermal Cyclic Reformer (ACR) based fuel processor and to integrate the fuel processor with a Proton Exchange Membrane (PEM) fuel cell. In the ACR reactor the heat required for the endothermic natural gas reforming reaction is obtained through exothermic oxidation of nickel (Ni)-based catalyst. Two ACR reactors cycling between reforming and regeneration steps are used to generate a continuous hydrogen (H<sub>2</sub>) rich stream called reformat. The reformat is cleaned-up using the downstream components which include the shift reactor and the preferential oxidation (PrOx) reactor. The final stream has clean hydrogen gas in it with less than 10 parts per million (ppm) carbon monoxide (CO). This makes it suitable for generating electricity with the PEM fuel cell.

GE Global Research (earlier GE Energy and Environmental Research) will design, optimize and validate a reliable and safe integrated distributed power system based on an ACR and a PEM Fuel Cell that has an electrical efficiency of at least 40% on a lower heating value (LHV) basis. The expected benefits include an installed capital cost of the system of less than \$1,200/kW (kilowatt) including a fuel processor cost of less than \$550/kW when the system is manufactured at a rate in excess of 5,000 units per year.

### **This project supports the PIER program objective of:**

- Improving the energy cost/value of California's electricity by developing a PEM fuel cell and ACR based Distributed Power Generation technology that is cost-effective.

### **Proposed Outcomes:**

1. The integrated prototype fuel processor will produce a hydrogen (H<sub>2</sub>) stream with a concentration of carbon monoxide (CO) less than 10 ppm in order to meet the requirements of the PEM fuel cell.
2. The fuel processor will be rated for 50 kilowatt electric (kWe).
3. The fuel processor will be integrated with a 5-10 kW PEM fuel cell.
4. The DPG system will have system availability in excess of 90%.
5. The DPG system will have an overall electric efficiency greater than 40% (LHV basis).

### **Project Status:**

The project is within budget and on schedule and is expected to achieve its goals and objectives. Project will be completed by December 2005.

## **Catalytic Combustion Retrofit of a Gas Turbine at Sonoma Development Center**

**Contract #:** 500-01-037

**Contractor:** California Department of Developmental Services

**Subcontractors:** Kawasaki Gas Turbines - Americas : Catalytica Energy Systems, Inc.

**Contract Amount:** \$105,000

**Match Amount:** \$1,492,148

**Contractor Project Manager:** Mary Lavin (707) 938-6932

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

The purpose of this demonstration project is to retrofit a 1.4 megawatt (MW) Kawasaki gas turbine at the Sonoma Developmental Center (SDC) in Eldridge, California, with the Catalytica Energy Systems (CESI) Xonon<sup>®</sup> catalytic combustor, which will reduce its nitrogen oxides (NO<sub>x</sub>) emissions from 30 ppm to less than 2.5 parts per million (ppm). The project will be the first commercial demonstration of this technology that was developed, in part, with Commission funding. It will provide “real world” performance and operations data on the Xonon technology and allow for comparison of the Xonon-equipped turbine’s performance with previous operations using water injection for NO<sub>x</sub> control, then “Dry-Low-NO<sub>x</sub>” abatement. The project will also provide the first field demonstration of the Commission’s newly developed microturbine test protocols.

SDC is the largest of five facilities operated by the California Department of Developmental Services. There are 800 developmentally disabled clients, plus a staff of 2,500 who provide 24-hour care. The facility encompasses 120 buildings, all of which use electricity and steam provided by a central power plant. This combined heat and power (CHP) system uses waste heat from a gas turbine to produce steam to heat buildings, operate sterilizers, and cook food.

### **This project supports the PIER Program objectives of:**

- Improving the environmental and public health costs/risks of California’s electricity by demonstrating advanced emissions control performance of a small industrial gas turbine operating under commercial conditions, without the use of toxic chemicals for exhaust gas clean-up.
- Improving the energy cost/value of California’s electricity by enabling use of small gas turbines for distributed generation in situations where the cost and footprint requirements of exhaust cleanup systems to meet the mandated emissions levels would be prohibitive.

### **Proposed Outcomes:**

1. Conduct a successful engine test of the ultra-low emissions technology using a small gas turbine model that is currently marketed commercially.
2. Demonstrate a catalytic combustion system that is economically preferred over all other commercially available options for achieving exhaust NO<sub>x</sub> levels below 2.5 ppm in a small industrial gas turbine.

### **Project Status:**

The Xonon-equipped turbine has been operating since January 2003 with NO<sub>x</sub> emissions from the turbine generally below 3 ppmv at 15% oxygen (O<sub>2</sub>), and usually below 2.4 parts per million by volume (ppmv). Total NO<sub>x</sub> emissions for the system average 3.8 ppmv when the duct burner for the heat recovery steam generator is operated. Before conversion to the Xonon combustion system, NO<sub>x</sub> emissions were approximately 30 ppm for a similar 1.4 MW Kawasaki gas turbine.

Over the same two-year operating period, the maintenance outage rate was 12%, mostly for components other than the Xonon combustion system. The catalyst in the first Xonon module was replaced after 4500 hours. The next catalyst remained in service 14 months and appeared to be only 75% spent when it was replaced.

The project is expected to be completed by March 2006.

## **Catalytic Combustor-Fired Industrial Gas Turbine**

**Contract #:** 500-01-045

**Contractor:** Solar Turbines Incorporated

**Subcontractors:** MRI : Catalytica Energy Systems, Inc.

**Contract Amount:** \$2,994,884

**Match Amount:** \$3,435,069

**Contractor Project Manager:** Kenneth Smith (619) 544-5539

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

The purpose of this project is to integrate catalytic combustion technology into Solar Turbine's Taurus 70, a 7.5 megawatt (MW) industrial gas turbine. As part of this project, Solar is working with a Catalytica Energy Systems (CESI) lean catalytic combustion system, Xonon™. A fully operational catalytic combustion system will be designed, procured, and evaluated at Solar's facility in San Diego. In parallel, Solar is also evaluating Alzeta's surface stabilized combustion and Precision Combustion's rich/lean catalytic combustion technologies. Eventually, Solar will select among the three emission reduction technologies, equip one of their turbines and conduct an engine test.

### **This project supports the PIER Program objectives of:**

- Improving the energy cost/value of California's electricity by reducing the cost of and environmental barriers to the use of distributed generation. This will reduce electric power costs for the public and private sectors, increase the electric capacity within the State, and enhance the reliability and quality of the State's power infrastructure.
- Improving the environmental and public health costs/risk of California's electricity by reducing emissions from gas turbines and through the creation of superior nitrogen oxides (NO<sub>x</sub>) reduction technologies.

### **Proposed Outcomes:**

1. Design, procure, and evaluate a fully operational catalytic combustion system at Solar's facility in San Diego.
2. Integrate catalytic combustion technology into Solar Turbine's Taurus 70, a 7.5 megawatt (MW) industrial gas turbine. This activity represents a key step in the implementation and commercialization of a <2.5 ppm NO<sub>x</sub> combustion technology for California-based gas turbines. The commercialization of this technology will spur the growth of distributed power generation and cogeneration in the State by providing a lower cost path to ultra-low NO<sub>x</sub> emissions compared to exhaust gas cleanup.

### **Project Status:**

Solar has completed in-house testing of the CESI Xonon catalytic combustor, and T70 engine testing with the Xonon combustor at the Caterpillar Technical Center near Peoria, Illinois. In both cases the Xonon system performed well and resulted in NO<sub>x</sub> emissions below 2.5 parts per million by volume (ppmv). As part of another PIER-funded project, Solar performed similar combustor and engine tests on Alzeta's low emissions technology. With DOE funding, Solar also tested the Precision Combustion technology. Early in 2005, Solar will down select one of the three technologies to carry forward to an in-house engine test.

## **Demonstration and Testing of Microturbine Generators (UCI - APEP)**

**Contract #:** 500-99-028 **Project #:** 1

**Contractor:** University of California, Irvine

**Project Amount:** \$604,866

**Contractor Project Manager:** G. Scott Samuelsen (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### **Project Description:**

The purpose of this project is to develop standardized performance testing and reporting procedures or protocols for microturbine generators (MTGs). Standardized protocols are being developed for heat rate or fuel-to-electricity conversion efficiency, atmospheric and acoustic emissions, and power quality.

The technical performance goals:

- Establish and use a stakeholder group to identify appropriate parameters for inclusion among the testing protocols and to review project deliverables.
- Develop a set of prescriptive testing and reporting methodologies that will result in uniform testing and reporting of MTG operation under specified operating conditions.

The economic performance goal:

- Accelerate the market penetration of MTGs by providing common methods for performance testing and reporting of test results.

### **This project supports the PIER Program objectives of:**

- Improving the reliability/quality of California's electricity by providing standardized MTG performance data that can be used by manufacturers to improve their products.
- Improving the environmental and public health costs/risks of California's electricity by providing standardized methods for measuring and reporting atmospheric emissions.

### **Proposed Outcomes:**

Standardized testing and reporting procedures for MTGs will:

1. Provide consistent MTG performance information regardless of who performs the testing.
2. Allow comparison between manufacturers' specifications and actual operation.
3. Indicate technology barriers limiting performance of MTGs and thereby identify opportunities for future research, development and demonstration.

### **Project Status:**

Technical work was completed in 2003. Performance testing and reporting protocols for MTGs have been developed, peer reviewed, and widely distributed in electronic and hard copies. They will be published as an appendix to the Final Report.

A Final Report that incorporates PIER contract manager comments will complete the project. The project results have been transferred to a joint US Department of Energy/multi-state collaborative, which is developing Nationally-accepted performance testing, and reporting protocols for microturbines, small turbines and reciprocating engines, in both electricity-only and combined heat and power applications.

## Demonstration of a Low emission Advanced Vortex Combustor

**Contract #:** 500-02-025

**Contractor:** National Energy Technology Laboratory

**Subcontractors:** Ramgen Power Systems

**Contract Amount:** \$999,696

**Contractor Project Manager:** Tom George (304) 285-4825

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### Project Description:

The purpose of this project is to demonstrate an Advanced Vortex Combustor that produces 3 parts per million by volume (ppmv) or less nitrogen oxides (NO<sub>x</sub>) emissions without after-treatment. This achievement would be a significant advancement in combustion technology applicable to many types of gas turbine engines. The joint partnership in this effort is advantageous, since it directly couples the fundamental knowledge gained from this effort with a commercial gas turbine entity, i.e. Ramgen Power Systems (RPS). RPS views the Advance Vortex Combustor as an essential part of their commercial engine design. California has long led the nation in pursuing environmentally superior technologies to provide power. Successful completion of this project will provide another breakthrough technology to California. By playing a direct role in the development of the Advanced Vortex Combustor, NO<sub>x</sub> emissions for the Ramgen cycle and other gas turbines could be reduced to regulated levels without the added expense and environmental hazards of exhaust after-treatment. An important additional consideration is the projected fuel-flexibility of the Advanced Vortex Combustor to effectively utilize unconventional fuels like biomass, land fill gas, and sub-quality gas reserves. The Advanced Vortex Combustor concept coupled with the Ramgen engine cycle has the realistic prospect of bringing significant benefits in terms of reliable low-cost low-emissions power to the people of California starting in 2005. This PIER supported project will advance the following:

- **Distributed Generation.** The combined capabilities of low emissions from an Advanced Vortex Combustor design, and the projected low cost/high efficiency of the Ramgen Turbine creates new opportunities for the California high tech industry to secure reliable power. Projections indicate that the Ramgen engine cycle may be the first engine in the 200 kilowatt (kW) to 5 megawatt (MW) range that can compete with wholesale power rates. The required foot-print is small relative to other alternatives. In addition, combined heat and power (CHP) applications of distributed generation create additional opportunities for major energy savings.
- **Increased Use of Industrial Waste Gases to Generate Electricity.** Major developmental efforts are underway to commercialize biomass-fueled integrated gasification and combined cycle (IGCC) systems. This is particularly important to both the U.S. Department of Energy and California. It is likely that the Advanced Vortex Combustor concept studied in this effort can be extended for use in a wide range of fuel applications.
- **Increased Use of Sub-Quality Gas Resources and Land Fill Methane.** The Gas Research Institute (GRI) estimates that one-third to one-half of the natural gas reserves in the lower-48 states, not associated with oil production, are sub-pipeline quality. Sub-pipeline quality gas contains contaminants above 4% and must be treated before delivery to a natural gas pipeline. The processing required to lower contaminants in sub-quality gas adds to the general production cost, and results in higher fuel costs. The projected capability of the Advanced Vortex Combustor to burn low quality gas, including gas with high nitrogen content, creates new opportunities for generating electric power.

- **Hybrid Turbine/Fuel Cell Systems.** Advanced Vortex Combustors will fit into power generating systems in many ways. For example, due to their simple, compact design, this combustor concept may be applied in a hybrid turbine/fuel cell system.

The overall technical goal of this project is to demonstrate an Advanced Vortex Combustor that produces 3 ppmv or less NO<sub>x</sub> emissions without after-treatment. This achievement would be a significant advancement in combustion technology applicable to many types of gas turbine engines. The specific, technical objectives upon which this project's success will be evaluated are:

- Minimizing NO<sub>x</sub> and other pollutant emissions.
- Optimization of the premixing strategy.
- Optimization of the flame stability (i.e., flame anchor at lean operating conditions).
- Sensitivity to combustion driven acoustic oscillations.
- Turndown and LBO limits.
- Robustness of ignition.

The overall economic/cost goal of this project is to achieve regulatory compliance using an Advanced Vortex Combustion concept without incurring cost of exhaust after-treatment. The specific, economic/cost objectives upon which project's success will be evaluated are:

- Provide fundamental knowledge and understanding to achieve less than 3 ppm NO<sub>x</sub> at a lower cost than existing alternatives.
- Exercise the design tools and evaluate an actual design at elevated pressure with realistic inlet air preheat.

**This project supports the PIER Program objectives of:**

- Improving the energy cost/value of California's electricity by jump-starting distributed generation.
- Improving the environment and public health cost/risk of California's electricity by achieving less than 3 ppm NO<sub>x</sub>.
- Improving the reliability/quality of California's electricity by providing an affordable, reliable alternative to upgrading or expanding the grid in California.

**Proposed Outcomes:**

1. Advanced Vortex Combustor for a gas turbine that produces 3 ppmv or less NO<sub>x</sub> emissions without expensive after-treatment alternatives for emission control.
2. Gas turbine in the 200 kW to 5 MW range that can compete with wholesale power rates and with a foot-print that is small relative to other alternatives.

**Project Status:**

Preliminary tests have shown excellent results achieving the project goals. The project is on schedule and within budget. The project will be completed by March 2005.



**Design, Construction, and Operation of a Power Module for High Efficiency, Low-Cost, Multi-Fueled 10-100 kW Solid Oxide Fuel Cells**

**Contract #:** 500-01-020

**Contractor:** Gas Technology Institute

**Subcontractors:** Materials and Systems Research, Inc. : Nexant, Inc. : University of Utah : Technologix Corp

**Contract Amount:** \$2,999,998

**Match Amount:** \$1,309,204

**Contractor Project Manager:** Kevin Krist (847) 768-0793

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

**Project Description:**

The purpose of this project is to design, fabricate, operate and test a 1-3 kW (kilowatt) sub-scale solid oxide fuel cell (SOFC) stack and balance of plant that have potential for low cost and high efficiency. The sub-scale module consists of a fuel cell stack, air pre-heater and pre-burner. The module will be the basis for 10-100 kW SOFC systems suitable for distributed generation combined heat and power (CHP) applications.

The project is based on SOFC system-design features that optimize both the electrochemical performance of the fuel cell stack and the transfer of stack-generated heat. The design features include a low air-to-fuel ratio, a low pressure drop across the stack, even flow and temperature distributions in a cross flow stack, and rectangular fuel cells radiating heat to an air pre-heater panel adjacent to the stack. Material and energy balances for the design indicate a potential for a natural gas-to-electricity conversion efficiency of 55 percent with an additional 35 percent of the fuel heat content available as high quality heat.

**The project supports the PIER Program objectives of:**

- Improving energy cost/value of California electricity by reducing the manufacturing cost and the efficiency of solid oxide fuel cells.
- Improving reliability and sufficiency of California's electricity by developing a distributed generation technology that can operate on different fuels and that can be sited in buildings within urban areas.
- Improving the environment and public health by generating electricity with carbon dioxide and water as the only significant emissions.

**Proposed Outcomes:**

1. Materials and material combinations that have the potential to achieve a cell power density of at least 0.7 W/cm<sup>2</sup> (watts per centimeter squared) operating on hydrocarbon fuels at 650°C.
2. A fuel cell stack with a power density of 0.4 W/cm<sup>2</sup> at 0.8V operating at 650°C. The fuel utilization target is 60-85% and the air utilization target is equivalent to 50% excess air. The air utilization target is an order-of-magnitude lower than typical requirements for stack cooling, and contributes to lower parasitic power consumption.
3. Power degradation of <0.6% per 1,000 hours for the 1-3 kW power module during 2,000 hours of operation near the design point.
4. Operation of three sub-scale power modules that demonstrate heat transfer, multi-fuel capability, reliability and thermal and load cycling performance for 50% electrical efficiency in 10 kW systems.



5. Verification that a three-dimensional stack model can accurately predict stack performance effects associated with parameters such as stack dimensions, reactant flow pattern, radiation heat transfer, volumetric power density, and secondary cooling effects.

**Project Status:**

The project is on budget and was nearing completion as of the end of 2004. The project is addressing issues such as methods for stack compression, cell contact aids, insulation materials and design, gas manifold design, sources of resistance within the stack, and the effects of electrode thickness, composition, structure and gradient on electrochemical performance of a cell. A 550 W stack integrated with an air preheater has been tested.

**Develop & Demonstrate MTG Combustion System Capable of Operating on Medium & Low Btu Gas and Liquid Fuels**

**Contract #:** 500-00-020 **Project #:** 2

**Contractor:** University of California, Irvine

**Project Amount:** \$528,895

**Contractor Project Manager:** G. Scott Samuelsen (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

**Project Description:**

The purpose of this project is to develop and demonstrate a Microturbine Generator (MTG) combustion system that is capable of operating on medium-BTU content gas, low-Btu content gas, and liquid fuel with low emissions and minimum impact on rated efficiency.

The Technical Objectives for the MTG combustion system, when used in a modified Capstone Turbine Corporation MTG, are:

- <10 ppmv nitrogen oxides (NO<sub>x</sub>) and carbon monoxide (CO) from 50-100% load at 100% rated efficiency on medium- and low-BTU fuels for a range of gas compositions.
- <10 ppmv NO<sub>x</sub> and CO emissions from 50-100% load at 80% rated efficiency on liquid fuels.

(Emission target levels are corrected to 15% oxygen under International Organization for Standardization (ISO) test conditions. Percent rated efficiencies are in comparison to rated efficiencies for the MTG operating on natural gas fuel.)

**This project supports the PIER Program objective of:**

- Improving the energy cost/value of California's electricity by demonstrating the fuel flexibility of MTGs.

**Proposed Outcomes:**

The anticipated benefits of this project are:

1. A publicly-available database of the emissions and efficiency of Capstone microturbines operating at partial to full load on four different fuels:
  - Natural gas (as the baseline).
  - Low-heat content synthetic gas (similar in chemical composition to gas from biomass gasification).
  - Medium-heat content synthetic gas (similar in chemical composition to landfill and sewage digester gas).
  - Liquid fuels (such as diesel fuel).
2. Validation of certain MTG performance testing protocols that were developed under Contract #500-99-028, Project 1.

**Project Status:**

The project is behind schedule because of the problems encountered in Project 1. The Design Reports for MTG operation on low-Btu, medium-Btu and liquid fuels were completed. Modified injectors were fabricated and were initiated.

**Develop Low NO<sub>x</sub> - Low CO MTG Combustor with Incremental Price Increase <20% of Standard Design**

**Contract #:** 500-00-020 **Project #:** 3

**Contractor:** University of California, Irvine

**Project Amount:** \$826,917

**Contractor Project Manager:** G. Scott Samuelsen (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

**Project Description:**

The purpose of this project is to develop and demonstrate a cost-effective low-emission combustor for a microturbine generator (MTG). The technical performance objectives are:

- Suitability for retrofit installation into a Capstone iCHP 60 kW combined heat and power system.
- Emissions of less than 3 parts per million by volume (ppmv) nitrogen oxides (NO<sub>x</sub>) and 10 ppmv carbon monoxide (CO) at 15% oxygen (O<sub>2</sub>) for 50-100% load operation on natural gas fuel and during start-stop mode.

The economic performance objective is an increase in capital cost of no more than 20% above that of a conventional combustor.

The combustor development is being done in collaboration with Capstone Turbine Corporation, a California-based MTG manufacturer.

**This project supports the PIER Program objective of:**

- Improving the energy cost and value of California's electricity by developing a combustor that will enable the siting of MTGs in accordance with the strictest air quality standards in the nation.

**Proposed Outcome:**

1. Develop a MTG combustor that produces emissions of less than 3 ppmv NO<sub>x</sub> and less than 10 ppmv CO at 15 percent O<sub>2</sub> when operating on natural gas over a 50 to 100 percent load range and during start-stop. Determine if the incremental price of MTGs using this combustor can be no more than 20 percent greater than standard designs.

**Project Status:**

Experimental and modeling studies have been conducted to determine the effects of air/fuel mixing, air/fuel ratios, and modified injectors on emission levels. A full combustor hardware apparatus has been fabricated and tested. A Capstone MTG has been purchased.

## **Development of a Partial Oxidation Gas Turbine for Combined Electricity and Hydrogen-Enriched Fuel Gas Production**

**Contract #:** 500-02-005

**Contractor:** Gas Technology Institute

**Subcontractors:** Solar Turbines Incorporated : Eclipse Combustion

**Contract Amount:** \$1,480,023

**Match Amount:** \$1,670,339

**Contractor Project Manager:** Joseph Rabovitser (847) 768-0548

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

The purpose of this project is to develop and demonstrate an ultra-high efficiency, environmentally superior and cost-competitive partial-oxidation gas turbine (POGT) system for combined electricity and high-temperature hydrogen-enriched fuel gas production suitable for application in a wide range of utility and industrial processes. After development of the 200 kilowatt electric (kW<sub>e</sub>) POGT, it will be field tested in combination with an existing industrial boiler or high temperature furnace in California.

### **This project supports the PIER Program objectives of:**

- Improving the energy cost/value of California's electricity by the development of a novel approach to using small turbines for on-site low-cost electric power generation that can be readily integrated with existing utility and industrial thermal processes for extremely high overall energy utilization efficiency.
- Improving environmental and public health costs/risk of California's electricity by demonstrating the POGT system's capability to significantly reduce nitrogen oxides (NO<sub>x</sub>) and carbon dioxide (CO<sub>2</sub>) emissions associated with gas-fired turbine-based power generation and existing thermal processes.

### **Proposed Outcomes:**

The overall economic/cost objective of this unique combined heat and power (CHP) project is to demonstrate POGT installed capital costs that are competitive with conventional small turbines and overall electricity production costs, including emissions controls that are significantly lower than for existing stand-alone turbines and hybrids.

Specific technical and economic performance targets include:

1. An increase in overall thermal efficiency of an integrated POGT-furnace system by 40%, and a POGT-boiler system by 25%.
2. Fuel to electricity efficiency in excess of 88%.
3. NO<sub>x</sub> emissions less than 3 parts per million by volume (ppmv) (@ 15% oxygen (O<sub>2</sub>)) for the POGT, and 50% to 70% reduction for industrial furnaces and boilers.
4. Significant CO<sub>2</sub> (a greenhouse gas) reduction by improved efficiency and fuel utilization.

### **Project Status:**

Working with subcontractors in southern California, GTI completed the design and manufacturing of a partial oxidation reactor (POR). It has been delivered to GTI's facility in Illinois and mounted in a test rig. Testing will begin early in 2005 and then the POR will be mounted on a Solar Turbines' Centaur 40, the gas turbine selected for modification to a POGT. Project partner Solar Turbines conducted a market evaluation of two important concepts for

industrial use of the POGT: (1) electricity and hydrogen production, and (2) electricity and synthesis gas production for further conversion of POGT product gas into synthetic liquid fuels.

## **Development of Steady-State Analytical Tools for Fuel Cells (UCI - NFCRC)**

**Contract #:** 500-99-028 **Project #:** 2

**Contractor:** University of California, Irvine

**Project Amount:** \$306,322

**Contractor Project Manager:** G. Scott Samuelsen (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### **Project Description:**

The purpose of this project is to develop steady state computer simulation modules and analysis strategies for fuel cell and fuel cell/turbine hybrid systems and cycles. Simulation modules for higher temperature fuel cells namely, solid oxide and molten carbonate fuel cells, and associated balance of plant components for fuel cell and fuel cell/turbine hybrid systems will be developed and integrated into a computer code. A graphical user interface and a web-based version of the code will be developed.

This project is a continuation of work started under a previous PIER Contract #500-98-052.

### **This project supports the PIER Program objective of:**

- Improving energy cost/value by applying the predictive capabilities of the analysis tools to guide future fuel cell and fuel cell/turbine hybrid system design and operation.

### **Proposed Outcomes:**

1. Develop a publicly-available computer code that incorporates a fundamental understanding of the processes and features of fuel cell systems.
2. The code will predict system performance and the effects of system design and operational changes on system performance.
3. The code will enable manufacturers to determine how to construct fuel cell and hybrid systems in order to reduce cost and complexity while retaining reliability.

### **Project Status:**

The modules have been integrated into a computer code named Advanced Power Systems Analysis Tools (APSAT). The technical work for this project was essentially complete in 2003. The Draft Final Report was submitted in April 2004. The Draft Final Report did not demonstrate that the APSAT code has been validated, which is a contractual requirement. A Final Report that addresses the Contract Manager's comments on the Draft Final Report has not been submitted.

Many of the materials properties, cell dimensions and cell designs are fixed and not changeable by outside users. As a result, APSAT will be most useful to universities in general and the University of California, Irvine in particular.

### **Dynamic Modeling of Fuel Cells and Hybrid Systems (UCI - NFCRC)**

**Contract #:** 500-99-028 **Project #:** 3

**Contractor:** University of California, Irvine

**Project Amount:** \$497,979

**Contractor Project Manager:** G. Scott Samuelson (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

#### **Project Description:**

The purpose of this project is to develop computer simulation modules to describe the dynamic operation of fuel cell and fuel cell hybrid electricity generating systems. Modules will be developed that describe the dynamic operation of a solid oxide fuel cell, a molten carbonate fuel cell, a gas turbine engine, a fuel reformer, and the balance of plant for a fuel cell/turbine system. Dynamic or transient operation includes system start-up and shutdown, electric load following, a change in fuel flow, composition, temperature or pressure, a change in gas turbine inlet and outlet conditions, and a change in turbine rotation speed. Data will be collected to verify the validity of the computer simulations.

#### **This project supports the PIER Program objective of:**

- Improving energy cost/value by developing the predictive capability for fuel cell and hybrid system operation so as to guide future generating system design.

#### **Proposed Outcomes:**

1. Develop a publicly-available computer simulation model that accurately describes the performance of a fuel cell or hybrid system during transient operating conditions.
2. The model will substitute for physical testing and will be especially useful as a substitute for physical testing under conditions that could damage system components.
3. The model will be used to screen hybrid system designs, probe the operating space of system configurations, evaluate impacts of component changes, and analyze operating problems.

#### **Project Status:**

This project is active. The simulation modules are complete, model validation is under way, and the computer model is being applied to various fuel cell and fuel cell hybrid system configurations. Model validation is occurring in part with data obtained on a 220 kilowatt (kW) solid oxide fuel cell/microturbine hybrid system that was partially funded under PIER Contract # 500-97-012, Project #7. Several professional papers have been submitted for publication.

## Experimental Study of Jet Mixing in Rich-Quench-Lean Combustors

**Contract #:** 500-00-025

**Contractor:** University of California, Irvine

**Contract Amount:** \$269,224

**Contractor Project Manager:** G. Scott Samuelsen (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### Project Description:

The purpose of this project is to obtain fundamental understanding of the mixing and reaction processes involved in the Rich-burn/Quick-mix/Lean-burn (RQL) combustion concept. The RQL concept is one technique for obtaining low nitrogen oxides ( $\text{NO}_x$ ) emissions from gas turbine combustors. Lean premixed combustion systems can achieve low  $\text{NO}_x$  and carbon monoxide (CO) emissions; however, combustion becomes unstable at the leanest conditions that minimize emissions. The RQL concept may be able to reduce unstable combustion conditions. The success of RQL depends on the mixing of air jets in the combustor's Quick-mix section with the fuel-rich gases coming from the Rich-burn section. The Contractor is performing experimental studies of jet mixing at the high-temperature high-pressure combustion conditions found in gas turbines. The detailed spatial characterization of the thermal and chemical flow fields coupled to modeling efforts will aid in optimizing the Quick-mix section for low  $\text{NO}_x$  formation while maintaining combustion stability.

### This project supports the PIER Program objective of:

- Improving energy cost/value of California's electricity by developing a robust combustor that produces few pollutants and that avoids combustion instability. The adoption of low  $\text{NO}_x$  and low CO combustors will facilitate the siting of gas turbines in California without the need for post-combustion emission reduction controls.

### Proposed Outcomes:

1. Characterization of the temperature and emissions fields within the jet-mixing section.
2. Understanding the means by which  $\text{NO}_x$  and CO are produced in the mixing section and relate this insight to the overall performance of the RQL combustor.

### Project Status:

The project is behind schedule and has expended the PIER contract budget. The contract was originally set to expire on March 31, 2005. It will be extended one year so that the contractor can finish the project but the budget will not be augmented. Contractor will complete the project with other sources of funding. The Test Plan, test hardware fabrication, and the experimental facilities preparation have been completed. Jet mixing tests at both atmospheric and elevated pressures have been completed. The elevated pressure test results compare favorably with empirical behavior and with prior atmospheric testing.



## Identifying Opportunities in Distributed Energy Markets

**Contract #:** 500-02-029 **Project #:** 4

**Contractor:** Gas Technology Institute

**Project Amount:** \$120,000

**Contractor Project Manager:** Mark Stevens (847) 768-0568

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### Project Description:

The goal of the Distributed Energy Collaborative Program (DECP) is to facilitate the deployment of new distributed generation (DG) technologies. GTI works with the participating members, consisting primarily of natural gas distribution companies, to plan and implement demonstration projects to assess the performance of new and emerging DG systems, such as fuel cells, microturbines, and advanced reciprocating engines. The DECP obtains real time performance data on DG equipment and makes the data available to DECP members via the internet. Additional information is made available via quarterly telephone conferences and final reports.

Projects currently underway include:

1. Fuel Cell Demonstrations.
2. DG Web Advisor.
3. Microturbine Performance Testing Program.
4. DG Strategic Service.
5. DG Guidebook.
6. National Accounts Energy Alliance (NAEA) Program.

### This project supports the PIER Program objective of:

- Providing improved reliability of electric supply system and the quality of delivered electricity by installing and testing emerging distributed generation systems.

### Proposed Outcomes:

The major activities under this project are:

1. Economic assessment.
2. Modeling and technical support.
3. Integration technology.
4. Emerging technology evaluation.

### Actual Outcomes in 2003:

1. Plug Power 5 kilowatt (kW) Proton Exchange Membrane Fuel Cell (PEMFC) Field Demo with the City Public Service of San Antonio at the Challenger Learning Center:
  - One-year demonstration commenced January 2003.
  - Cell Stack replacements in May and September because the stacks could not maintain at least 2.5 kW or the efficiency dropped below 18%.
2. Fuel Cell Technology Solid Oxide Fuel Cell (SOFC) Field Demo with Memphis Light, Gas & Water (MLGW) at the Memphis Botanic Garden (MBG):
  - Contractor Bid Packages have been prepared and issued to local contractors.
  - A site visit and pre-bid meeting was held in December, 2003.

3. Microturbine Performance Testing Program:
  - Capstone 330 DETC Lab Test – Complete.
  - Capstone 330 Field Demo in Riverhead, NY – Ongoing.
  - Ingersoll-Rand PowerWorks DETC Lab Test – Complete.
  - Turbec T100 DETC Lab Test – Complete.
  - Capstone C60 DETC Lab Test – Complete.
  - Discussions for the final Microturbine test have commenced. Originally, a Bowman 80kW unit was going to be tested. It is possible that a Kohler 80 kW unit will be tested.
  - Ingersoll-Rand PowerWorks Field Demo with Alagasco at HealthSouth.
    - Testing of Beta Unit terminated Nov.'02.
    - Testing of Production Unit Started Dec.'02.
    - Turbine Overhauled June '03.
    - The demonstration has been completed.
4. National Accounts Energy Alliance (NAEA) Program:

Five distinct test and verification projects fall under this effort and each project is in a different stage of development.

  - 1) The 200 Market Street office building in Portland, Oregon, (27 kW microturbine, Unifin heat recovery heat exchanger, 10 RT Yazaki hot-water-activated absorption chiller) project is complete.
  - 2) The A&P supermarket Capstone 60 microturbine, Unifin heat recovery heat exchanger and a Munters Desiccant Dehumidifier project in Hauppauge, Long Island, New York, ran December 4-5, 2003 and then was repaired and restarted December 29, 2003.
  - 3) The HEB supermarket Bowman/Elliott Microturbine Broad Absorption Chiller project is awaiting a commitment from the developer.
  - 4) The Cinemark theater CHP/desiccant equipment is installed and operating in Plano, Texas. DTE has offered to replace the Stirling engine with 75 kilowatt electric (kW<sub>e</sub>) internal combustion engine.
  - 5) The Walgreen's (50 kW Generac auto derivative natural gas-fueled engine, SEMCO desiccant cooler) site in Pinellas Park, Florida is awaiting the final design review meeting January 6.

**Actual Outcomes in 2004:**

1. Plug Power PEM Fuel Cell Field Demo with CPS San Antonio at Brooks City Base:
  - Testing completed. The final report is being prepared.
2. Fuel Cell Technology SOFC Field Demo with Memphis Gas, Light and Water at Memphis Botanic Garden:
  - Technical issues, including the inability to operate above 3 kW, arose during a 300 hour laboratory test of the Beta 1 unit. Field delivery postponed until issues have been resolved.
3. Microturbine Performance Testing Program:
  - Turbec T100 Field Test at the Suffolk Country Forensic Science Center in Long Island, New York – Site preparation, remote monitoring equipment installation, turbine installation and commissioning were completed in February. Numerous equipment failures constrained operation.

- A Kohler 80 kW microturbine field test is planned at a Southern Connecticut Natural Gas LNG peaking facility. The site survey has been completed. The microturbine has been delivered to GTI for laboratory performance testing.
  - Ingersoll-Rand 70 kW PowerWorks with heat recovery field test with Alagasco at HealthSouth in Birmingham, AL is under way and is being monitored.
4. National Accounts Energy Alliance (NAEA) Program:  
Five distinct test and verification projects fall under this effort and each project is in a different stage of development.
- The 200 Market Street office building in Portland, Oregon, (27 kW microturbine, Unifin heat recovery heat exchanger, 10 RT Yazaki hot-water-activated absorption chiller) project is complete.
  - The A&P supermarket Capstone 60 microturbine, Unifin heat recovery heat exchanger and a Munters Desiccant Dehumidifier field test in Hauppauge, Long Island, New York is being monitored.
  - The Cinemark theater CHP/SEMCO integrated active desiccant equipment is installed and operating in Plano, Texas. A conventional system is operating side-by-side as a control.
5. Stirling Engine Demonstration Test:
- GTI placed the order for the 55 kW Stirling Thermal Motors (STM) Stirling Engine in early July. GTI has prepared a Draft Test Plan and is preparing the Final Test Plan. GTI is working with Questar on selecting a field test site in its service territory in Utah.

**Current Status:**

The project is expected to be completed by June 2005.

## **Integrated Gas Production and Handling System for Renewable Fuel Simulation**

**Contract #:** 500-00-020 **Project #:** 1

**Contractor:** University of California, Irvine

**Project Amount:** \$991,695

**Contractor Project Manager:** G. Scott Samuelsen (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### **Project Description:**

The purpose of this project is to develop a gas production and handling system with the ability to simulate various fuel gas compositions – including fuel gases from renewable and industrial sources – sufficient to operate distributed generation (DG) systems up to 250 kW in size. The gas production facility will be able to mix and deliver fuel mixtures containing known proportions of natural gas, nitrogen, carbon dioxide, carbon monoxide and hydrogen. The simulated gas mixtures will be used to test DG systems in Project 2 of this contract.

### **This project supports the PIER Program objective of:**

- Improving the energy cost/value of electricity by creating the ability in California to test DG systems under laboratory conditions on a variety of simulated fuels. Fuel flexibility in DG operation permits the use of biomass-derived and waste fuels that may be less expensive and/or less polluting than natural gas.

### **Proposed Outcome:**

1. Ability to test and verify the performance of DG systems on various known fuel compositions.

### **Project Status:**

The project is behind schedule because of difficulty in obtaining a production system for hydrogen and carbon monoxide that meets the gas volume requirements within the contract budget. An alternative gas production approach has been proposed and approved for implementation.

**Low Cost, High Efficiency, Ultra-Low NO<sub>x</sub> ARICE Solution Using HCCI Combustion**

**Contract #:** 500-02-003

**Contractor:** Lawrence Livermore National Laboratory

**Subcontractors:** University of California, Berkeley : Ricardo, Inc.

**Contract Amount:** \$1,999,017

**Match Amount:** \$600,000

**Contractor Project Manager:** Daniel Flowers (925) 422-0529

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

**Project description:**

The purpose of this project is to develop an engine generator set that uses a homogenous charge compression ignition (HCCI) system and operate the engine generator set for more than 1,000 hours. In an HCCI engine, the combustion occurs due to the compression of the homogenous charge. The peak combustion temperature is relatively low, thus reducing nitrogen oxides (NO<sub>x</sub>) emissions. If successful, this project will demonstrate a reciprocating engine technology that is the best distributed generation solution (in terms of emissions, efficiency, and cost) for the below-5 MW market that can be ready for sale in 2005.

**This project supports the PIER Program objectives of:**

- Improving the efficiency and reducing the cost of distributed energy resources by developing an engine generator set that uses a homogenous charge compression ignition (HCCI) system.
- Improving the environment, public health and safety by helping reduce electricity generation emissions.
- Providing products and choices to California consumers for near-term DG applications.

**Proposed Outcome:**

1. This project will eliminate the cost (approximately \$1000/kW) of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on reciprocating engines. This will provide superior NO<sub>x</sub> performance at costs far below the cost of Selective Catalytic Reduction (SCR) and other alternate NO<sub>x</sub> control technologies.

**Project Status:**

This project is on schedule and within budget.

## Low NO<sub>x</sub> GT Combustor

**Contract #:** 500-00-004

**Contractor:** Alzeta Corporation

**Subcontractors:** Solar Turbines Incorporated : National Energy Technology Laboratory :  
Honeywell, Inc. : University of California, Irvine

**Contract Amount:** \$1,311,768

**Match Amount:** \$2,740,000

**Contractor Project Manager:** Neil McDougald (408) 727-8282

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### Project description:

The purpose of this project is to continue advancement of Alzeta's surface stabilized combustion technology to build monolithic injectors for application in industrial- and micro-scale gas turbine engines. Development will include formulation of improved monolithic injector design and manufacturing methods, rig testing of the improved monolithic injector in micro- and industrial-scales, and engine testing of the improved monolithic injector in a microturbine generator.

The overall technical goal of this project is to bring to market readiness a gas turbine monolithic injector utilizing surface-stabilized combustion technology. The monolithic injector will be commercialized under the trade name Gas Turbine Semi-radiant Burner (GTSB).

The specific, technical objectives upon which this project's success will be evaluated are:

- Successful casting of monolithic injectors, which removes all solid-metal parts from the combustor.
- Successful development and product demonstration of monolithic injectors for microturbine generators manufactured by Honeywell.
- Successful development of monolithic injectors for industrial engines manufactured by Solar Turbines.
- On-engine emissions performance of < 5 parts per million by volume (ppmv) nitrogen oxides (NO<sub>x</sub>) (15% oxygen (O<sub>2</sub>)) and < 10ppmv carbon monoxide (CO).

The overall economic/cost goal of this project is to produce a commercial product that is cost competitive with existing dry low NO<sub>x</sub> combustors and superior to Selective Catalytic Reduction (SCR) systems while providing emissions performance superior to both.

The specific, economic/cost objectives upon which the project's success will be evaluated are:

- Eliminate \$100/kW cost of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on industrial-scale engines.
- Provide superior NO<sub>x</sub> reduction performance at costs on a par with the best available dry low NO<sub>x</sub> combustors for micro-scale gas turbine engines.

### This project supports the PIER Program objective of:

- Improving the environment, public health and safety a California's electricity by producing a commercial product that is cost competitive with existing dry low NO<sub>x</sub> combustors and superior to SCR systems while providing emissions performance superior to both.

**Proposed Outcomes:**

1. Eliminate \$100/kW cost of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on industrial-scale engines.
2. Provide superior NO<sub>x</sub> reduction performance at costs on a par with the best available dry low NO<sub>x</sub> combustors for micro-scale gas turbine engines.

**Project Status:**

This project is on schedule and within budget. The project will be completed by February 2005. The micro-turbine part of this project has been on hold since February 2002 due to Honeywell's decision not to pursue microturbine development.

## Reduced Temperature SOFCs Operating on Direct Oxidation of Natural Gas

**Contract #:** 500-01-014

**Contractor:** Lawrence Livermore National Laboratory

**Contract Amount:** \$3,000,000

**Match Amount:** \$6,000,000

**Contractor Project Manager:** Cynthia Atkins-Duffin

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### Project Description:

The purpose of this contract was to develop a commercially viable planar solid oxide fuel cell (SOFC) system with high reliability, high power density, low degradation rate and high efficiency.

SOFCs operate at 1,000°C (1,832°F). The high temperature is dictated by the need for high ionic conductivity of the electrolyte, which is achieved only at higher temperatures. The high temperature of operation and the need to cycle between ambient temperature and operating temperature causes thermal stresses on the fuel cell components with consequent crack formation.

Lower operating temperatures would permit the replacement of certain ceramics with metals thereby lowering costs, making fabrication easier and increasing durability. However, suitable alternative materials must be identified and fabrication methods must be developed.

### The project supports the PIER Program objectives of:

- Improving energy cost/value of California electricity by reducing the manufacturing cost and improving the efficiency of solid oxide fuel cells.
- Improving reliability and sufficiency of California's electricity by developing a distributed generation technology that can operate on different fuels and that can be sited in buildings in urban areas.
- Improving the environment and public health by generating electricity with carbon dioxide and clean water as the only significant emissions.

### Proposed Outcomes:

1. An integrated fuel cell system that meets all economic and field application requirements.
2. A metal cell interconnect that is highly conductive and is compatible with other fuel cell components.
3. New sealant materials that connect piping to the fuel cell stack without leakage.
4. New materials, designs and fabrication techniques for the electrolyte, anode and cathode. Demonstration of a single cell with a peak power density greater than 0.7 W/cm<sup>2</sup> at 650°C.
5. An improved proprietary stack design achieved by means of computer modeling.
6. An anode that directly oxidizes hydrocarbon fuels without the need for a separate reformer.
7. Achievement of an \$800/kW cost target for a complete SOFC system.
8. Successively larger fuel cell stacks, culminating in a 10 kW stack. The 10 kW stack will be integrated with a complete balance of plant system, and the integrated system will be operated as a stand-alone generating system.



**Project Status:**

The Contractor began work. The PIER Contract Manager stopped work in May 2003 and terminated the contract in 2004 because the key subcontractor was unable to obtain match funding for \$4,800,000.

### **Solid Oxide Fuel Cell (SOFC) Project – Phase III**

**Contract #:** 500-02-029 **Project #:** 3

**Contractor:** Gas Technology Institute

**Subcontractors:** Materials and Systems Research, Inc.

**Project Amount:** \$140,000

**Contractor Project Manager:** Kevin Krist (847) 768-0793

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

#### **Project Description:**

GTI and its partners are developing small, technically workable, solid oxide fuel cell (SOFC) systems. The specific SOFC technology involved is termed RTESP because it operates at *reduced-temperature* (600 to 800°C) and the cell is *electrode-supported* and *planar*.

This project is evaluating the performance of RTESP SOFC stacks under internal reforming conditions. Internal steam reforming within a SOFC stack is an attractive option for cost reduction, effective thermal management, and high efficiency. However, internal reforming of the higher hydrocarbons in natural gas can lead to carbon formation in the anode. In addition, higher degrees of internal reforming can lead to large temperature gradients caused by the fast reforming reaction at the fuel inlet. These temperature gradients can damage components or interfaces by thermal stress. For these reasons, a pre-reforming step is normally required. The ratio between internal and pre-reforming is best optimized on the basis of experimental data.

GTI is evaluating electrochemical performance, cell endurance, and requirements for preventing carbon formation under direct internal reforming (DIR) conditions and the extent of pre-reforming required as a function of cell operating conditions.

#### **This project contributes to the PIER program objective of:**

- Improving the reliability, quality, and sufficiency of California's electricity by providing small-scale high-efficiency solid oxide fuel cells for the distributed generation market and by demonstrating new technologies that provide high-quality reliable power.

#### **Proposed Outcome:**

1. Evaluate the electrochemical performance and degradation of anode-supported, planar SOFC's under direct internal reforming (DIR) conditions in the range of 700-800°C. A total of 10 tests, 5 with 35-cm<sup>2</sup> and 5 with 100-cm<sup>2</sup> cell packages, are planned. For most of these single-cell tests GTI will employ 100% methane as fuel while a few selective cells will be operated on sulfur-free natural gas.

#### **Actual Outcome:**

1. An initial test provided a baseline for the characteristics, performance, and endurance at 800°C of a tri-layer fuel cell package (90-cm<sup>2</sup> active area, 0.032-in thick, 5.5"x 5.5" single cell) under DIR conditions and using methane as fuel. Four cell tests at different steam-to-methane ratios have been completed. Cell performance is being evaluated.

#### **Current Status:**

This project is expected to be completed by June 2005.

## Testing and Demonstration of Two 25kW Stirling Engines

**Contract #:** 500-01-025 **Work Authorization #:** E2I-WA-007

**Contractor:** Electricity Innovation Institute

**Subcontractors:** Professional Energy Solution, Inc.

**Project Amount:** \$143,118

**Match Amount:** \$143,118

**Contractor Project Manager:** David Thimsen (650) 855-2548

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### Project Description:

The purpose of this project is to determine and report on the performance (efficiency plus emissions), durability, availability maintainability and general suitability for commercial service of an ENX 55 Stirling engine manufactured by Stirling Thermal Motors (STM). The 55 kW (kilowatt) STM engine was introduced for commercial service in 2004. The engine will operate on water treatment facility digester gas.

### This project contributes to the PIER program objective of:

- Reducing the cost of electricity and increasing the value by providing a low cost, external combustion, fuel flexible engine that has low emissions.

### Proposed Outcomes:

1. Field performance that meets or exceeds the manufacturer's specifications.
2. Achieve component lifetimes, long term durability of major components, and overall performance stability required for economic viability in commercial operation.

### Project Status:

The project is active. The project is behind schedule because of financial problems experienced by STM during 2003. The Inland Empire Utilities Agency (IEUA) Regional Treatment Plant RP-5 has been selected as the demonstration site. The Stirling engine has been ordered, and delivery is expected in February 2005. The demonstration period will be at least one year.

## **The Testing, Optimization & Demonstration of an (EPAG) Microturbine**

**Contract #:** 500-01-012

**Contractor:** ALM Turbine, Inc.

**Subcontractors:** Optimized Turbine Solutions : Alturdyne : Parametric Solutions :  
Atlantic Precision

**Contract Amount:** \$2,867,270

**Match Amount:** \$3,405,443

**Contractor Project Manager:** Boris Glezer (858) 481-5977

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

The purpose of this project is to use a combination of novel technologies to improve the performance of a 300 kW microturbine. The technologies include the following:

- A new low-cost recuperator.
- Advanced blade cooling strategies.
- Combustion methods to control the formation of polluting emissions.
- Power turbine designs that cut mechanical losses.

The project will analyze the performance of prototype systems, upgrade their designs, proof-test the upgraded designs in a prototype engine, and then build three beta-test engines for laboratory and field testing.

### **This project supports the PIER Program objectives of:**

- Improving the energy cost/value of California's electricity by fostering the use of distributed generation (DG) in a way that will increase local electricity supply reliability, reduce costs and reduce peak demand on the power grid.
- Improving the reliability/quality of California's electricity by developing and demonstrating a highly reliable microturbine with significantly increased efficiency and increased power quality with both full and partial loads.
- Improving the environment and public health by reducing emissions from microturbines used as a distributed energy resource.

### **Proposed Outcomes:**

1. Thermal efficiency at full load increased from 24-30 percent to 37.5-40 percent.
2. Part-load efficiency of at least 30 percent at 15 percent power and relatively high efficiency over a power range of 50-400kW.
3. Emissions of <5 ppm (parts per million) nitrogen oxides (NO<sub>x</sub>), <20 ppm carbon monoxide (CO) and no unburned hydrocarbons (UHC).
4. Availability of >90 percent with a life of 40,000 hours and mean time between overhauls of 15,000 hours.
5. High responsiveness to sudden load and speed changes.
6. The elimination of a number of life-limiting parts found on many gas turbines.
7. A turbine geometry that can be used for a family of engines from 75kW to 500kW.
8. Multi fuel capability (three premiums and one bio-derived).
9. Cost range of \$500-600 per kW.

**Project Status:**

This project has not begun and no PIER funds have been spent because the Contractor never completed prerequisite R&D work. Instead, the Contractor submitted a significantly revised Work Statement. The Commission has reviewed the new Work Statement and is evaluating whether or not the project should be terminated.

## Ultra-Low NO<sub>x</sub> Combustion System for a 13.5 MW Gas Turbine Generator

**Contract #:** 500-01-010

**Contractor:** Alzeta Corporation

**Subcontractors:** Solar Turbines Incorporated

**Contract Amount:** \$2,404,310

**Match Amount:** \$1,076,510

**Contractor Project Manager:** Neil McDougald (408) 727-8282

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Active

### Project Description:

The purpose of this project is research and development in the area of ultra-low emissions combustion control for industrial gas turbine engines (e. g., Solar Turbines' Titan 130 or Taurus 70). This project fits into a continuum of ultra-low emissions developments in previous PIER contracts with Alzeta (500-97-031 & 500-00-004). The work under this contract includes combustor materials and manufacturing development, lab testing, engine testing, and field-qualifying demonstration of the low nitrogen oxides (NO<sub>x</sub>) gas turbine combustor system. The results of this contract will help California increase distributed generation capacity without sacrificing environmental quality considerations.

### This project supports the PIER Program objectives of:

- Improving the environment and public health by accelerating development of an ultra-low NO<sub>x</sub> combustion system.
- Improving the energy cost/value of California's electricity by reducing the capital cost of ultra-low NO<sub>x</sub> gas turbines and providing competitive technology for ultra-low emissions.

### Proposed Outcomes:

1. Develop an ultra-low NO<sub>x</sub> nanoStar combustion system for Solar Turbines' Titan 130 or Taurus 70 gas turbine and demonstrate successful operation in an industrial gas turbine. (Solar Turbines' Titan 130 and Taurus 70 engines have very similar combustion system requirements as both operate at the same pressure ratio and turbine inlet temperature.)
2. Achieve the following technical and economic performance goals:
  - < 3 ppm NO<sub>x</sub> emissions.
  - 10 ppm CO emissions.
  - 10 ppm UHC emissions.
  - 26,000 hours serviceable life.
  - Incremental cost of less than \$150,000 per engine.
3. Eliminate \$100/kW cost of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on industrial-scale engines.
4. Provide superior NO<sub>x</sub> performance at costs on a par with the best available dry low NO<sub>x</sub> combustors for micro-scale gas turbine engines.

### Project Status:

This project is on schedule and within budget. Preliminary testing of the combustor hardware in a test rig has shown significant promise of achieving the technical and economic goals. The project will be completed by December 31, 2005.

## **Xonon Ultra-Low Combustion in Small Multican Turbines**

**Contract #:** 500-01-030

**Contractor:** Catalytica Energy Systems, Inc.

**Contract Amount:** \$2,997,986

**Match Amount:** \$3,420,613

**Contractor Project Manager:** Graydon Whidden (480) 556-5543

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Active

### **Project Description:**

The purpose of this project is to develop a catalytic combustion system that is economically preferred over all other options for achieving exhaust nitrogen oxides (NO<sub>x</sub>) levels below 3 parts per million (ppm) in a small multi-combustor gas turbine, without the need for exhaust gas cleanup devices. The intent is to conduct a successful engine test on a gas turbine that is currently marketed commercially. PIER has supported development of the catalytic combustor for single-combustor turbines, so this project will expand the application of this technology to a much broader market that includes multi-combustor turbines.

### **This project supports the PIER Program objectives of:**

- Improving the environmental and public health costs/risks of California's electricity by enabling attainment of emissions levels below current regulatory limits, without the need for exhaust cleanup systems, which are more costly and potentially hazardous.
- Improving the energy cost/value of California's electricity by enabling use of small gas turbines for distributed generation in situations where the cost and footprint requirements of exhaust cleanup systems to meet the mandated emissions levels would be prohibitive, and where there is local resistance to the introduction of toxic chemicals used for exhaust gas cleanup.

### **Proposed Outcome:**

1. NO<sub>x</sub>, carbon monoxide (CO), and unburned hydrocarbon emission levels (at 15% oxygen (O<sub>2</sub>)) below 3 ppm, 10 ppm, and 10 ppm, respectively, at simulated loads from 80% to 100% of the turbine's rated power output.

### **Project Status:**

To address size constraints on multi-combustor engines, Catalytica reduced the length of the Xonon module by 31%, and to improve original equipment manufacturer (OEM) acceptance they improved preburner turndown ratio and controls to compensate for catalyst aging. However, market conditions in the power generation industry have made it impossible for Catalytica to find a gas turbine OEM partner for this project. Nonetheless, informal collaboration with several OEMs brought to light issues that would make Xonon® a stronger and more attractive candidate as the preferred ultra-low NO<sub>x</sub> solution in their product lines. These suggestions included improved catalyst performance (reduced aging and activity degradation) and reduced product cost.

Because of demonstrated success of the Xonon technology at Silicon Valley Power and Sonoma Developmental Center – it has reduced NO<sub>x</sub> emissions to less than 3 ppm without exhaust gas cleanup – the project was modified so that Catalytica could:

- Improve manufacturing methods to improve product uniformity, increase yield and reduce waste.
- Reduce the complexity of manufacturing.

Accomplishments in these areas have enabled Catalytica to reduce product cost and improve catalyst performance, which reduces end-user maintenance time for catalyst replacement. For example, at the Sonoma Developmental Center the Xonon-equipped gas turbine went into service in January 2003 and the catalyst was replaced after about six months. The next catalyst remained in service 14 months and appeared to be only 75% spent when it was replaced.

The project will be completed by June 2005.



## **EPAG Projects Completed in 2004**

## **Distributed Energy Resources (EPRI Program #101)**

**Contract #:** 500-02-028 **Project #:** 19

**Contractor:** Electric Power Research Institute (EPRI)

**Project Amount:** \$117,435

**Contractor Project Manager:** David Thimsen (650) 855-2548

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Active

### **Project Description:**

This project provides financial and operational analysis of distributed resource (DR) applications. Distributed resources are small generation (1 kilowatt (kW) to 50 megawatt (MW)) and/or energy storage devices typically sited near customer loads or at distribution and sub-transmission substations. Distributed resources provide grid, system, or customer benefits such as electricity supply reliability, standby generation, peak shaving, combined heat-and-power (CHP), prime power, premium power, or renewable power.

The distributed resource technologies considered were fuel cells, internal combustion engines, small gas turbines, microturbines, and energy storage systems. Topics considered were Integration of DR into the power infrastructure, DR applications, and DR markets and customer needs.

The focus during 2004 was on the use of biogas and opportunity fuels, packaged combined heat and power systems, and the ability of DR generating technologies to meet California Air Resources Board 2003 and proposed 2007 atmospheric emissions limits.

### **Proposed Outcomes:**

1. Produce seven Strategic Intelligence Updates.
2. Update the database of DR technologies, which is available on the internet at:  
⇒ [www.disgen.com](http://www.disgen.com)
3. Perform a fuel cell technology development update and benchmarking of small fuel cell companies.
4. Perform a technology assessment of residential power generators.
5. Perform a technology assessment of the emerging low emission DER technologies.
6. Produce a technical update on mobile generation technologies.

### **Actual Outcomes:**

1. Produced eight Strategic Intelligence Updates called, Strategic Intelligence Update: Technology Development, Vol. 5, No. 1-8: Emerging Distributed Generation Technologies and Infrastructure. Available on the web at:  
⇒ [www.epri.com/](http://www.epri.com/).
2. DR Web Technology Database Updates. EPRI Product #s E215151; 1008429; 1011485.
3. Fuel Cell Technology Development Update and Benchmarking of small fuel cell companies. EPRI Product ID #s 1008432; 1011471; 1011472; 1011464.
4. Technology assessment completed. Residential Combined Heat and Power Systems. EPRI Product ID #1011485.
5. Technology assessment of emerging low emission DR technologies. Planned for 3/31/2005. EPRI Product ID #1011341.
6. Technical update on mobile generation technologies. Planned for 3/31/2005.
7. Reciprocating Engines and Combustion Turbines: EPRI Product ID # 1011486.
8. 101.018 Microturbines and Stirling Engines. EPRI Product ID# 1008430.

**Project Status:**

The project was completed in December 2004.

## **EPAG Projects Completed in 2003**

## **Catalytic Combustor - Fired Industrial Gas Turbine for Distributed Power & Cogeneration Applications**

**Contract #:** 500-98-041

**Contractor:** Solar Turbines Incorporated

**Subcontractors:** Catalytica Energy Systems, Inc.

**Contract Amount:** \$814,543

**Match Amount:** \$773,391

**Contractor Project Manager:** Kenneth Smith (619) 544-5539

**Commission Contract Manager:** John Henry Beyer Ph.D. (916) 654-4609

**Status:** Completed

### **Project Description:**

The primary goal of this project, a joint effort between Solar Turbines Incorporated and Catalytica Energy Systems, Inc. (CESI), was to select the preferred conceptual design of a catalytic combustion system for a natural gas-fired industrial gas turbine. Catalytic combustion has demonstrated the ability to reduce gas turbine NO<sub>x</sub> emissions from their current levels (9 to 25 ppmv) to sub-3 ppmv levels (@ 15% O<sub>2</sub>), without the use of water or steam injection, or the use of any post-combustion NO<sub>x</sub> reduction. The industrial gas turbine originally selected for this project was the 5.2 MW Taurus 60, but was later changed to the 7.5 MW Taurus 70, a new Solar product deemed to have better market potential for the catalytic technology. This project was the first of three phases of development. Subsequent phases – conducting hot testing of the combustor assembly and actual operation on a gas turbine – are continuing under PIER Contract #500-01-045.

### **This project supported the PIER Program objectives of:**

- Improving the reliability and quality of California's electricity by eliminating harmful pollutants and allowing these gas turbines, to be used in distributed generation applications.
- Improving the energy cost/value of California's electricity by introducing industrial gas turbines with catalytic combustion, rather than the higher-cost option of post-combustion treatment systems such as selective catalytic reduction (SCR).
- Improving the environment and public health cost/risks of California's electricity by incorporating pollution prevention that is potentially more effective at reducing NO<sub>x</sub> and CO emissions than post combustion pollution clean-up.

### **Proposed Outcomes:**

1. Bring to market readiness, a catalytic combustion system that is cost competitive with other commercially available NO<sub>x</sub> reduction technologies for industrial scale gas turbines.
2. Develop and then integrate the optimum preburner, premixer, catalytic core and burn out zone liner designs into the Taurus 70 gas turbine.
3. Implement a control system strategy for the catalytic combustion system capable of handling start-up, shutdown, load following, and full load loss without damage to the combustor or gas turbine.
4. Produce a commercial product that provides cost effective NO<sub>x</sub> control that meets permitting requirements in the most restrictive air quality districts.
5. Reduce the capital cost of NO<sub>x</sub> control for the Taurus 70 gas turbine by 80% compared with exhaust cleanup using SCR. This will result from completion of this three-phase project.

In its efforts to develop a catalytic combustion system for its Taurus 60, and more recently Taurus 70, industrial gas turbines, Solar has delivered a final report for this contract describing progress in developing the necessary component technologies and engineering designs for the pre-burner, fuel-air premixer, catalytic core, burnout zone liner, engine hardware, and control system. Solar has also written a preliminary production readiness plan.

**Project Status:**

This project was terminated ahead of schedule due to changes in the direction of Solar's research efforts. As a result, there were minor scope reductions in some tasks, and one task concerning experimental evaluation of combined premixer and pre-burner performance was not undertaken. A final project report (P500-03-045) dated April 2003 describing the R&D work accomplished was submitted to the Commission. Solar is building upon all of the knowledge gained in this contract and is continuing these efforts to implement ultra low emissions technology in its Taurus 70 gas turbine in a follow-on Commission contract (#500-01-045) entitled *Catalytic Combustor-Fired Industrial Gas Turbine*.

## **DER Technologies Assessment and Databases**

**Contract #:** 500-02-028 **Project #:** 7

**Contractor:** Electric Power Research Institute (EPRI)

**Project Amount:** \$49,000

**Contractor Project Manager:** Dan Rastler (650) 855-2521

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Completed

### **Project Description:**

This project provides financial and operational analysis of distributed resource (DR) applications. Distributed resources are small generation (1kW to 50MW) and/or energy storage devices typically sited near customer loads or distribution and sub-transmission substations. Distributed Resources provide grid, system, or customer benefits, such as standby generation, peak shaving, combined heat-and-power (CHP), prime power, premium power, or renewable power.

Distributed Resource technologies and topics included in this work:

- DR generating technologies such as fuel cells, internal combustion engines, small gas turbines, energy storage, and microturbines.
- Integration of DR into the power infrastructure.
- DR applications.
- DR markets and customer needs.

The focus during this year was on the use of biogas and opportunity fuels, packaged combined heat and power systems, and the ability of DR technologies to meet California Air Resources Board 2003 and proposed 2007 atmospheric emissions limits.

### **Proposed Outcome:**

1. An updated database of DR technologies, which is available on the internet at: [www.disgen.com](http://www.disgen.com).

### **Actual Outcomes:**

1. Strategic Intelligence Update: Technology Development, Emerging Distributed Generation Technologies and Infrastructure, September 2003, EPRI Product #1009120.
2. Strategic Intelligence Update: Technology Development, Emerging Distributed Generation Technologies and Infrastructure, October 2003, EPRI Product #1009121.
3. Strategic Intelligence Update: Technology Development, Emerging Distributed Generation Technologies and Infrastructure, November 2003, EPRI Product #1009122.
4. DR Web Technology Database Updates: In progress, Completion expected March 31, 2004, EPRI Product #1005010.

### **Project Status:**

The Commission's participation in this project ended December 31, 2003.

## **EPAG Projects Completed in 2002**



## **75-kW MCFC Power Plant Verification Test Project**

**Contract #:** 500-97-039

**Contractor:** M-C Power Corporation

**Subcontractors:** San Diego Gas and Electric Company : Bechtel National, Inc. : Alternative Energy Systems Consulting, Inc. : Stewart and Stevensen

**Contract Amount:** \$1,000,000

**Match Amount:** \$1,956,841

**Contractor Project Manager:** Thomas Benjamin (630) 986-8040

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Completed

### **Project Description:**

The purpose of this project was to demonstrate the energy-producing performance of advanced design molten carbonate fuel cell (MCFC) stack components in a 75 kW electric power generator. The test was conducted at an existing test facility at Marine Corps Air Station Miramar in San Diego. Based on information from a prior Miramar test and small-scale factory tests, advances in fuel cell components and stack design have been identified. A new 75 kW stack incorporating the advanced technology was installed at Miramar for testing.

### **This project supports the PIER Program objectives of:**

- Improving environmental and public health costs/risk of California's electricity by developing an efficient electric generating technology that emits negligible levels of ozone and smog precursor pollutants and reduced levels of carbon dioxide.
- Improving the reliability/quality of California's electricity by demonstrating fuel cell technology for distributed generation applications.

### **Proposed Outcomes:**

1. Verify the long-term current density performance of M-C Power's most advanced stack design in full size cells under field conditions.
2. Evaluate the effect of anode recycle on generator performance.
3. Gather operating data upon which to base the design of future commercial prototype generators.
4. Achieve a 50-80 percent higher efficiency than conventional combustion-type generators.

### **Actual Outcomes:**

1. M-C Power, Inc. successfully completed nearly 5 months of testing of its integrated, pressurized molten carbonate fuel cell (MCFC) power plant technology.
2. The MCFC power plant operated for about 3,300 hours and generated 250 MWh of electricity. The power system generation consistently exceeded the 75 kW rating throughout the test period.
3. Nitrogen oxide emission levels were below 0.4 ppm, which verified significant environmental benefits of MCFC technology.
4. System performance exceeded expectations and provided valuable design and operating information that is essential for the design of a commercial unit.

### **Project Status:**

The project has been completed.

## **A Novel Steam Reforming Reactor for Fuel Cell Distributed Power Generation**

**Contract #:** 500-97-038

**Contractor:** Energy and Environmental Research Corporation

**Subcontractors:** Phillips Petroleum Company

**Contract Amount:** \$349,852

**Match Amount:** \$303,458

**Contractor Project Manager:** Jerald Cole (714) 859-8851

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Completed

### **Project Description:**

The purpose of this project was to further develop a novel steam reforming process to convert natural gas to a hydrogen-containing mixture on a small scale. There are two novel aspects of the patented technology. First, the reformer and its catalyst are heated internal, thereby eliminating the need for an external furnace. Second, a carbon dioxide absorber is mixed with the reforming catalyst. This improves product gas quality, improves thermodynamic efficiency, and reduces the cost of the reformer. The intended market for the reformer is as the hydrogen source for a residential proton exchange membrane fuel cell (PEMFC).

### **This project supports the PIER Program objectives of:**

- Improving the reliability/quality, improving the environmental and public health costs/risks.
- Improving the energy cost/value of California's electricity by advancing the use of low-emission, low-cost, distributed resource fuel cell technologies.

### **Proposed Outcomes:**

1. Extending the catalyst and absorber life (greater than 5,000 hour).
2. Hydrogen production volume exceeding 25,000 cubic feet per day.
3. 75-85 percent conversion efficiency of fuel to hydrogen.
4. Low atmospheric emissions (especially important because the fuel cell stack itself has negligible emissions).
5. Cost targets that would make PEMFCs competitive with centralized power generation.

### **Actual Outcomes:**

1. A catalyst with a projected lifetime greater than 4,350 hours was developed.
2. The catalyst exceeded the 50 percent utilization goal by 22 percent.
3. Only one carbon dioxide absorber, commercial dolomite, was identified as being suitable.
4. Some of the technical objectives were not achieved because the pilot reformer had insufficient steam production (steam is needed in the reforming reaction) and inadequate reactant preheating.
5. Engineering analyses suggest that the project objectives can be achieved with further development efforts.

### **Project Status:**

Project is complete.

## Advanced Fuel Cells

**Contract #:** 500-00-022 **Project #:** 2

**Contractor:** Gas Technology Institute

**Project Amount:** \$102,500

**Match Amount:** \$2,050,000

**Contractor Project Manager:** Kevin Krist (847) 768-0793

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Completed

### Project Description:

The purpose of this project is to develop low-cost, very efficient, planar solid oxide fuel cells (SOFCs), operating at 650 – 800 °C (1,112 °F – 1,472 °F). The overall project includes the following activities:

- GTI Project # 30799: *SOFC Component Development, System Design, and Product Definition* – Project is developing small SOFC for a range of residential, commercial, and gas-utility applications. Involves advanced components and materials, and the design, assembly, and proof of feasibility testing of prototypes. Fuel is initially reformed externally and unit is air-cooled. GTI is working with Versa Power Systems.
- GTI Project # 30755 and 40823: *RTEP SOFC System Definition Study* – A limited, 2-year activity involving exploratory R&D on alternative system designs. Conducted by GTI and supported with GTI and CEC Advanced Fuel Cell Membership funds.
- GTI Project # 40492: *Design, Construction, and Operation of a Power Module for High Efficiency, Low-Cost, Multi-Fueled 1-3 kW Solid Oxide Fuel Cell* – Development of a 1-3 kW sub-scale module that employs (1) radiant heat transfer to reduce airflow, increase efficiency and reduce cost and (2) stack that operates near 650 °C on multiple fuels. Module consists of a stack, air pre-heater panel, and burner. Fuel is internally reformed.
- *Low-cost, efficient, planar SOFC operating at 650 °C* – Component and system development with Versa Power and University of Pennsylvania.

The goal of this project is to provide a low-cost, clean, efficient fuel cell technology for GTI member companies, the public, and government and other entities requiring effective distributed power generation.

### This project supports the PIER Program objectives of:

- Improving the energy cost/value of California's electricity by helping further developments within the fuel cell industry lead to overall lower costs of fuel cells.
- Improving the environment, public health and safety by developing an energy-producing technology that has negligible emissions and waste stream.
- Improving California's electrical system's reliability/quality/sufficiency by developing a clean distributed energy resource.
- Strengthening the California economy by helping California become a world leader in developing and using fuel cell technology.
- Providing greater choices for California consumers to both generate and consume electricity.

**Proposed Outcomes:**

1. A manufacturable, cost-effective, reliable, fuel cell stack technology capable of high power density in the operating temperature range of 650 - 800°C that meets the following criteria:
  - Operates for between 10,000 and 40,000 hours under steady-state, “always-on” conditions.
  - Operates with a to-be-determined number of thermal and load cycles.
  - Operates with stacks that are “gas-tight”, exhibiting voltage degradation rates <0.5% per thousand hours of operation.
  - Operates with a to-be-determined multi-fuel capability, but probably including natural gas, hydrogen, and methanol. Oxidation of other fuels, including dry hydrocarbons, will be investigated.
2. Development and implementation of 2- and 3-dimensional models for predicting stack performance.
3. Development and implementation of stack-model-integrated, system design models.
4. Development of a system design for market entry products that are aimed at acceptable cost and high reliability in small production volumes. Generation efficiencies can be relatively low, but attractive for the applications envisioned.
5. Development of a system design that is targeted at low-cost and high efficiency in larger production volumes through the use of improvements in heat and flow management and internal reforming.
6. Development of 1-3 kW prototypes exhibiting the characteristics listed above.

**Actual Outcomes:**

1. GTI Contract # 40492: *Module for High Efficiency, Low Cost, Multi-Fueled 1-3 kW Solid Oxide Fuel Cell*—Completed:
  - Modeling of radiant air pre-heating in the sub-scale module.
  - Experimental confirmation of radiant air pre-heating effect.
  - Initial stack flow mal distribution analysis.
  - Initial stack spatial temperature distribution analysis.
  - Effect of flow pattern on temperature distribution.
  - Design of facility for testing sub-scale module (To be installed in 2003).
2. GTI Contract # 30799: *SOFC Component Development, System Design, and Product Definition* – Completed:
  - Initial design of a 500W unit.
  - Fabricated and tested system components including reformer, burner, and hot assembly shell component.
  - Completed initial stack flow mal distribution analysis.
  - Initial flow and temperature distribution analysis.
  - Initial testing of hot module unit minus the stack.
3. *Low-cost, efficient, planar SOFC operating at 650 °C* – Completed:
  - Tested internally manifolded stacks up to 400W. Operated small, 2”x2” stacks up to 0.7W/cm<sup>2</sup> for 300 hr with thermal cycling and minimal voltage loss. Operated small stacks on hydrogen, neat methanol, ethanol/water, and reformat. Scaled stacks up from 2”x2” to 4”x4”. Shifted focus to new flat-plate stack design that is easier to fabricate and has improved sealing efficiency. Key stack design and metallic interconnect patents issued.
  - Operated copper-based, anode-supported cells on dry CH<sub>4</sub>, C<sub>4</sub>H<sub>10</sub>, decane, C<sub>7</sub>H<sub>8</sub>, and synthetic diesel with reduced tendency for carbon deposition. Results have implications for operating fuel cells directly on liquid hydrocarbons, but the research

is still at a very early stage. GTI and the University of Pennsylvania have submitted patent applications and some claims have issued. A GTI venture partner has formed a development company, Franklin Fuel Cells that is now conducting a technology development program.

4. GTI Contracts #40823 & 30755: *RTESP SOFC System Definition Study* –
  - Phase I: Identified early-entry markets with attractive financial, reliability and emissions-reduction characteristics. Defined initial fuel cell products – a 500W, stand-alone power supply providing continuous power and a 2-3 kW power supply capable of limited thermal cycling. Designed and modeled two initial SOFC systems using HYSYS (commercial process-design software). The system design was extended to a number of different process cases.
  - Phase II: Evaluated a stack design concept involving radiant heat transfer and low airflow.
  - Determined limits to the use of radiant heat transfer for reducing excess air needed for thermal management.
  - Developed an analytical expression for the maximum air temperature increase resulting from stack radiation. Applied the evaluation to a sample 1060 W case that utilized low airflow. Showed that stack radiation – instead of excess airflow - can produce the majority of the required air pre-heating. Established a framework for determining the need for a pre-burner to supplement radiant air pre-heating.
  - Extended the analysis to consider the effect heat loss to the surroundings and stack size has on the heat available for air preheating. The heat available for air pre-heating declines sharply in smaller units when using expected amounts of heat loss to the surroundings.
  - Completed the final report.

**Project Status:**

The project has been completed.

## Distributed Generation

**Contract #:** 500-00-022 **Project #:** 3

**Contractor:** Gas Technology Institute

**Project Amount:** \$178,500

**Match Amount:** \$3,570,000

**Contractor Project Manager:** John Kelly (847) 768-0665

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Completed

### Project Description:

The purpose of this project is to identify the application characteristics and technical requirements for the strategic utilization of gas-fired distributed generation beyond the electric distribution substation, near the point of use. The overall project includes the following activities:

- Distributed Energy Research (DER) Technology Research.
- Distributed Energy Technology Center (DETC).
- DETC – Building Cooling and Heating and Power (BCHP).

The goal of this project is to facilitate the development of distributed energy products for a wide range of residential and commercial sector applications.

### This project supports the PIER Program objective of:

- Improved reliability of electric supply system and the quality of delivered electricity.

### Proposed Outcomes:

1. Construction and startup of the GTI DETC in Des Plaines, Illinois.
2. Testing of advanced technology distributed generation systems, focusing on microturbines and reciprocating engines.

### Actual Outcomes:

1. DER Technology Research.
  - DG Reliability software has been completed and sent to Energy Nexus. Oak Ridge National Laboratory is using this software in support of the Laboratory's effort to create a reliability database.
  - Sustainable Urban Energy Design research and development work was started in March 2002. This program is a comprehensive look at developing a national model for sustainable urban design for 2100, with a goal of minimal or no emissions of greenhouse gases from the city.
    - Initiated the San Diego Urban Design Program with a press release and a conference in that City with representatives from GTI, Sempra, the Mayor of San Diego, various regional supporters, and a representative from the Mexican government. This is part of an international competition.
    - This is now an ongoing GTI Research Collaboration project, with participation by the Energy Commission, San Diego Regional Energy Office, Sempra, City of Philadelphia, Gas Company of Hawaii, municipal gas companies, and others.
2. DETC (New 3,000-kW Lab).
  - Construction of the DETC was completed. The facility successfully underwent shakedown tests and is now operational.
  - The Caterpillar and Cummings reciprocating engines to be housed in this facility were received and are operational.

- The first engine tested was for the Chicago Museum of Science and Industry, a Cummins, 1750 kW engine. Testing is complete and the unit was shipped back to the Museum.
  - The Turbec microturbine unit was installed and tested in the new lab. Overall, the Turbec unit worked very well.
  - GTI has received the Capstone 60 kW microturbine and intends to install and test this unit at the DETC during the first quarter of 2003.
3. DETC – BCHP Systems.
- Preparation work for the testing of a Capstone 30 kW – Takuma Chiller performance test was completed. The unit is now in the second-generation design phase.

**Project Status:**

The project has been completed.



## Durability of Catalytic Combustion Systems

**Contract #:** 500-97-033

**Contractor:** Catalytica Combustion Systems, Inc.

**Contract Amount:** \$1,316,303

**Match Amount:** \$3,290,846

**Contractor Project Manager:** Tom Morjig (650) 940-6371

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Completed

### Project Description:

The purpose of this project is to conduct the research and development necessary to advance catalytic combustion technology for on-engine field testing in a 1.5 MW Kawasaki (KHI) gas turbine engine. The technology must have demonstrated high durability and reliability for fast market acceptance. To accomplish this goal, Catalytica will operate the currently developed Kawasaki combustor in a power generation facility for 8000 hours (1 year). In addition, Catalytica will continue to develop the technologies necessary to achieve commercial level of durability and reliability for the KHI combustor and catalyst module.

Once reliability has been demonstrated, the Kawasaki combustor will be moved to commercial sites for field-testing. Finally, the Kawasaki combustor will be offered as a commercial product and begin translation of the technology to other gas turbine engines. The project goal is to improve energy cost and value of California's electricity market by creating a cost-competitive alternative to conventional NO<sub>x</sub> mitigation and reduction technologies for gas turbines in all size ranges.

### This project supports the PIER Program objectives of:

- Improving the reliability and quality of California's electricity by eliminating harmful pollutants and allowing gas turbines, which offer higher reliability compared to the current generating fleet, to compete in a deregulated market.
- Improving the energy cost/value of California's electricity by introducing catalytically-fired, industrial scale gas turbines that will decrease the cost of electricity compared to the higher cost option of these gas turbines equipped with post-combustion treatment systems such as selective catalytic reduction.
- Improving the environment and public health risks of California's electricity by incorporating pollution prevention rather than a pollution clean-up technology that is potentially more effective at reducing NO<sub>x</sub> and CO emissions by eliminating them from formation during combustion.

### Proposed Outcomes:

This project will eliminate \$100/kW cost of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on industrial-scale engines, and will provide superior NO<sub>x</sub> performance at costs on a par with the best available dry low NO<sub>x</sub> combustors for micro-scale gas turbine engines.

### Actual Outcomes:

1. Brought to market readiness a catalytic combustion system that is cost competitive with other commercially available NO<sub>x</sub> reduction technologies for industrial-scale gas turbines.



2. Lab tested the catalytic combustion system under actual engine service conditions to validate the adequacy of all components of the design and to establish durability during an 8000-hour performance test.
3. Completed the computation fluid dynamics (CFD) studies of the fuel-air mixer system that will improve the design by improving performance and reducing cost for the final commercial engine.
4. Lab tested to determine the effect of variability in gas fuel composition on catalyst performance.
5. Produced a commercial product that provides cost effective NO<sub>x</sub> control that meets permitting requirements in the most restrictive air quality districts. The catalytic combustion system resulting from this project has a lower capital cost than selective catalytic combustion systems for the turbine engines with comparable NO<sub>x</sub> control.

**Project Status:**

The project's first commercial application is at Sonoma Center in California. Kawasaki is offering Catalytica's catalytic combustor in its gas turbine.

### Emerging Distributed Resource Technologies - Program 33

**Contract #:** 500-00-023 **Project #:** 40-43

**Contractor:** Electric Power Research Institute (EPRI)

**Subcontractors:** Gas Technology Institute : Nexant, Inc. : Energy International, Inc. : ADI Thermal Power Corporation : American Electric Power : PowerCo US, Inc. : Arthur D. Little, Inc. : National Rural Electric Cooperative Association : Power Computing Systems : Rolls-Royce, Inc. : Southern California Edison : EPRI PEAC Corporation

**Project amount:** \$379,927

**Match amount:** \$1,382,994

**Contractor Project Manager:** Doug Herman (650) 855-1057

**Commission Contract Manager:** Jairam Gopal (916) 654-4880

**Status:** Completed

Fundamental Information about Distributed Energy Resources

33.001: DER Technology Assessments

33.002: Strategic Intelligence on Emerging DER Technology

33.003: DER Technology Business Venture Forum

Engines and Turbines for Grid Support

33.004: Technology Development Watch and Data: Engines and Small Gas Turbines

33.005 Monitoring and Validation of Field Applications: Engines and Small Gas Turbines

33.006: Business Case for DER Grid Support

Microturbines and Mini-Energy Storage

33.010: Validated Performance/Durability Data on Microturbine and Mini-Storage Products

33.011: Annual Microturbine and Mini-Storage Technology and Vendor Assessment

33.012: Integrated Microgeneration and Storage Concepts

Fuel Cells

33.013: Solid Oxide Fuel Cell R&D—Hybrid, Cogeneration, and Low-Temperature Systems

33.014: Residential Power Generator Technical Evaluation

33.015: Stationary Fuel Cell System Derived from Automotive R&D

33.016: Molten Carbonate Fuel Cell Systems: Technology Update

#### **Project Description:**

The purpose of this project is to promote the potential that distributed energy resources (DER) have to provide a substantial portion of the energy alternatives now demanded by California electricity users. Both energy service providers and customers need accurate and unbiased information on the benefits and liabilities associated with commercially available and emerging distributed resource technologies. DER technologies offer third-party energy service providers and energy customers innovative solutions to their energy service needs. EPRI's Emerging DER Technologies program provides detailed information on commercially mature reciprocating engines and gas turbines, and emerging microturbines and fuel cell systems technologies. To gather this information, EPRI assesses advanced DER components, performs technology validations, and leads pre-commercial development of technologies that offer high pay-off. As a member, the Energy Commission obtains intelligence in three distinct areas: rapid changes in technology, development of new distributed resources, and post-R&D commercialization initiatives. This program examines a balanced portfolio of near, intermediate, and long-term options.

**This project supports the PIER Program objectives of:**

- Improving the reliability/quality of California's electricity by developing generation options that energy providers can utilize to provide unique solutions for peaking power issues, to enhance system reliability (system voltage control), and to assure power quality to their customers.
- Improving the energy cost/value of California's electricity by assisting in the development of innovative distributed resource technologies that can potentially provide lower delivered cost electricity than central station power.
- Improving the environmental and public health costs/risks of California's electricity by assisting in developing fuel cell systems and other environmentally preferred generation technologies to replace traditional central station power.

**Proposed Outcomes:**

1. Perform DER technology assessments including current status, potential for improvements, critical components and issues, and the likelihood of success.
2. Deliver unbiased accurate strategic intelligence on emerging DER technologies to increase customer choice and enable competition.
3. Organize and conduct a DER technology business venture forum to allow participants to learn about new technology developments and market trends.
4. Demonstrate a novel control and dispatching hardware/software system for distributed generation.
5. Track and review current developments in microturbine and mini-energy storage technologies and vendors.
6. Perform independent assessments that evaluate vendor claims.
7. Explore and evaluate promising new concepts for integrating microgeneration and energy storage.
8. Evaluate the technical and business potential of emerging next-generation solid-oxide fuel cell technologies, including hybrid, cogeneration, and low-temperature systems.
9. Test the capabilities of small power systems for residential use.
10. Exploit fuel cell developments in automotive markets for high-value commercial and small industrial stationary DR applications.
11. Follow and develop information from field tests of molten carbonate fuel cells being conducted around the United States and overseas.

**Actual Outcomes:**

1. DER Technology Assessments.
  - A technical report—*Performance Testing of a Flywheel-Based Uninterruptible Power Supply* (1004444)—was published that provides complete details of performance testing of the UPS system, including test instrumentation and setup, test results, and overall conclusions. The system offers an innovative power quality solution for a broad range of industrial and commercial applications. It provides stored energy, immediately available, to protect critical loads against temporary power disturbances such as outages, sags, and surges.
  - A technical report—*Stirling Engine Assessment* (1007317)—was published that presents a summary of the technical trends, commercialization status, and economic viability of Stirling engine technology for distributed generation applications. While fuel cells and microturbines have received a majority of the recent focus, Stirling engine technology is beginning to receive more attention as a viable, and potentially competitive, distributed generation option.

2. Strategic Intelligence on Emerging DER Technology.
  - Six issues of an informative intelligence report—*Strategic Intelligence Update: Technology Development*—were published, providing up-to-date news and expert analysis of emerging DER technologies and trends—both domestic and internal.
3. DER Technology Business Venture Forum.
  - A high-level professional conference on venture capital financing of emerging energy technology firms, specifically those related to distributed resources, was held in July 2002 in Boston. It provided a forum for utilities, energy companies, equipment manufacturers, and vendors to discuss the latest technology, market, and policy developments. A report—*Report on the EPRI Business Venture Forum 2002: Whither Capital Markets for DR?* (1004445)—was published that summarizes and characterizes presentations made at the forum.
4. Control and Dispatching Software/Hardware.
  - The project team installed a control and dispatching system for distributed generation at the Lovelace Medical Center in Albuquerque, New Mexico and documented the system's operation. A technical report, *Novel Distributed Generation Control and Dispatching System: Application Validation and Benefits Quantification* (1004448), describes the system, which allows the connection of multiple generators at a number of sites to a utility control and monitoring system for the purpose of providing peaking power for the utility. Using distributed generation for this purpose is a potentially cost-effective solution to localized power system constraints caused by the inability to increase power transmission into an area experiencing steady growth in local power demand.
5. Microturbine and Mini-Storage Technology and Vendor Assessment.
  - The project team developed a technical review report, *Microturbine and Mini-Storage Technology and Vendor Assessment—Annual Update* (1004454), which includes vendor profiles and product timing information, as well as technology performance, application, and operating characteristics.
6. Integrated Microgeneration and Storage Concepts.
  - The project team conducted engineering design, cost, and test analysis research on existing technology concepts for integrating microgeneration and energy storage. A web-based report, *Integrated Distributed Generation and Energy Storage Concepts* (1004455), was produced that describes the performance benefits of combining microturbines and other distributed generators with various energy storage concepts.
7. Solid Oxide Fuel Cell (SOFC) R&D—Hybrid, Cogeneration, and Low-Temperature Systems.
  - To help guide future R&D investments in fuel cell hybrids, EPRI undertook a study with DOE to investigate the future market potential for fuel cell hybrids in the United States. The study's main goal was to evaluate the scale, efficiency, and performance relationships of fuel cell hybrids to satisfy market needs and to quantify the market potential under a competitive electricity market scenario. A report, *Fuel Cell Hybrids: Market Assessment and Early Adopter Study* (1007096), presents the study results, which will be useful in shaping future product requirements and establishing research and development goals.
  - A technical update report, *SOFC Technology Development* (1004457) was published that describes development and test results as well as technological and economic assessments of emerging SOFC applications, including hybrid SOFC-combustion turbines, SOFC-based cogeneration, and low-temperature planar SOFCs.
  - A technical report—*1 MW Fuel Cell Project: Test and Evaluation of Five 200 kW Phosphoric Acid Fuel Cell Units Configured as a 1 MW Power Plant* (1007014)—

was published that describes a demonstration of the new technology that is needed for utility management and control of multiple fuel cell power plants at a single location in an assured power application.

- The project team continued 2001 work to evaluate polymer electrolyte membrane residential power generators and to define and test SOFC systems for residential power. Findings—including performance, cost, and durability information—are presented in a web-based technical review document, *Residential Power Generation Technical Evaluation* (1004457).
8. Stationary Fuel Cell System Derived from Automotive R&D.
    - Researchers gathered information on performance, cost, and durability, which will be presented in a technical report, *Stationary Fuel Cell System Derived from Automotive R&D* (1004458), scheduled for publication in March 2003.
  9. Molten Carbonate Fuel Cell Systems: Technology Update.
    - The project team followed a series of MCFC field tests conducted in the United States and overseas and developed information on current activities, as well as durability, performance, interconnectivity, and related issues. Findings are presented in a technical review publication, *Molten Carbonate Fuel Cell Systems Technology Update* (1004459), scheduled for publication in March 2003.

**Project Status:**

The project has been completed.

**Energy Efficient, Low Emission, Cost Effective MicroPilot Ignited Natural Gas Engine Driven Genset for Deregulated, Distributed Power Generation Market**

**Contract #:** 500-97-041

**Contractor:** Gas Research Institute

**Subcontractors:** BKM, Inc.

**Contract Amount:** \$982,528

**Match Amount:** \$250,000

**Contractor Project Manager:** Lou Lautman (847) 768-0760

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Completed

**Project Description:**

The purpose of this project is to develop a new technology which takes advantage of the cost and emissions benefits of clean burning natural gas, the fuel efficiency of modern diesel engines, and the low first cost of high production diesel engines to further the use of internal combustion engines in distributed generation. This technology is known as MicroPilot diesel-cycle natural gas engine.

If successful this project will eliminate \$100/kW cost of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on reciprocating engines, and will provide superior NO<sub>x</sub> performance at costs on a par with or lower than the best available control technology, i.e. Selective Catalytic Reduction, for low NO<sub>x</sub> engines.

**This project supports the PIER Program objectives of:**

- Improving the reliability/quality of California's electricity by making lower cost, more reliable and better quality electrical power available via distributed generation where it is not possible to do so under central power generation approaches.
- Improving the energy cost/value of California's electricity by providing expected energy cost under \$0.04/kWhr and installed cost under \$200/kW.
- Improving the environmental and public health costs/risks of California's electricity because there is no known or suspected adverse impacts to the environment, citizen's health or safety resulting from this project or the commercialization of this technology.

**Proposed Outcomes:**

1. Complete development of a 1- percent MicroPilot engine.
2. Demonstrate a production ready version of the MicroPilot technology applied to the very popular Caterpillar 3412 diesel generator set engine. The MicroPilot technology developed and demonstrated under this project will be offered to Caterpillar (and all other OEM manufacturers) for commercialization.

**Actual Outcome:**

None. The project results could not be applied in California due to a change in California Air Resources Board emission regulations for distributed generation technologies.

**Project Status:**

The project ended with \$77,922 remaining unspent. That amount was returned to the PIER account.

## Low NO<sub>x</sub> Gas Turbine Combustors for Distributed Power Generation

**Contract #:** 500-97-031

**Contractor:** Alzeta Corporation

**Subcontractors:** Solar Turbines Incorporated : Honeywell, Inc. : FETC

**Contract Amount:** \$878,788

**Match Amount:** \$675,000

**Contractor Project Manager:** Scott Smith (408) 727-8282

**Commission Contract Manager:** Dave Hatfield (916) 654-7119

**Status:** Completed

### Project Description:

The purpose of this project is to develop, test, and demonstrate Surface Stabilized Combustor (SSC) that is reliable, quiet, compact, and operates with low NO<sub>x</sub>, CO, and unburned hydrocarbon emissions. Our research focused on the development of the GTSB into a commercial product. Gas turbine engines play an important role in the generation of efficient, low cost electric power and process heat for applications ranging from small 75-kilowatt (kW) distributed power systems up to 200-megawatt (mw) utility combined cycle power plants. Currently, market acceptance of gas-turbine-based distributed power systems and co-generation systems is hampered by their inherently high nitrogen oxide (NO<sub>x</sub>) emissions that necessitate the use of expensive, temperamental, and maintenance-intensive NO<sub>x</sub> control strategies such as steam injection and selective catalytic reduction (SCR). Efforts have been made to reduce gas turbine emissions at lower cost by using lean premixed combustion or Dry Low NO<sub>x</sub> (DLN) techniques. DLN combustors are designed to reduce thermal NO<sub>x</sub> emissions by burning with large amounts of excess air. So far, however, successful commercialization of DLN combustors has been limited by issues of noise, large size, durability, and cost as well as by the difficulties in maintaining consistent low emissions performance. During work on prior contracts, the concept of the Surface Stabilized Combustor (SSC) was developed, and a new product, the Gas Turbine Semi-radiant Burner (GTSB) emerged. A number of combustor prototypes were manufactured and tested under simulated gas turbine conditions. Testing of the GTSB occurred at the Federal Energy Technology Center (FETC), Honeywell Engine Systems (Honeywell), and Solar Turbines. While flame stability was sometimes difficult to achieve, we obtained a wealth of positive emissions data. Simultaneous low NO<sub>x</sub> and carbon monoxide (CO) (sub nine parts per million (ppm)) were reached at every pressure from 1 to 12 atmospheres (atm). Both NO<sub>x</sub> and CO were measured under one ppm at various times throughout the testing.

If successful, this project will eliminate \$100/kW cost of additional emissions control equipment currently required for NO<sub>x</sub> mitigation on industrial-scale engines, and will provide superior NO<sub>x</sub> performance at costs on a par with the best available dry low NO<sub>x</sub> combustors for micro-scale gas turbine engines.

### This project supports the PIER Program objectives of:

- Improving the environment, public health and safety.

When the GTSB is commercialized in gas turbine engines, it will provide the State of California with:

- Improved fuel efficiency through enabling clean, cost effective, high efficiency cogeneration to remain competitive in the face of increasing NO<sub>x</sub> controls.
- Lower fuel usage due to potential elimination of SCR that requires ammonia derived from natural gas.



- Reduced cost of power due to reduced capital and operating costs associated with production of peak power.
- Reduced environmental pollutant emissions from industrial and power generation facilities.
- Improved capital utilization that reduces power costs and improves industrial competitiveness.
- Products manufactured in California creating jobs and economic activity.

**Proposed Outcomes:**

This project continued to develop, test, and demonstrate SSC that is reliable, quiet, compact, and operates with low NO<sub>x</sub>, CO, and unburned hydrocarbon emissions. Our research focused on the development of the GTSB into a commercial product. The technical and economic objectives of the project were to develop a SSC with the following characteristics:

- Operation with preheat temperatures up to 1000°F and excess air levels exceeding 100 percent without bypassing.
- Reliable ignition, off-speed stability, and turndown over a suitable range of operating pressures, including an operational turndown ratio of 4:1.
- NO<sub>x</sub> emissions from the burner of less than 9 ppm corrected to 15 percent oxygen, meeting or exceeding the best available control technology (BACT).
- Combustor pressure losses no greater than currently acceptable levels (three percent to six percent of operating pressure).
- Life cycle cost that yields a NO<sub>x</sub> reduction cost factor of less than \$1,000 per ton of controlled NO<sub>x</sub>.
- Extremely low levels of CO and unburned hydrocarbons.
- Extreme thermal shock resistance to tolerate instantaneous fuel cut off at full load.
- Ease of inspection and field maintenance.

**Actual Outcomes:**

Several new combustors were designed, each representing a significant improvement in manufacturing techniques and engineering features. Initial testing of combustors was performed in Alzeta's 50 kW pressurized test facility. Successful results featuring superior emissions led to a demonstration of the technology at Honeywell (formerly AlliedSignal). The combustor was tested in a rig that qualifies combustors for use in the Parallon 75 engine (formerly the TurboGenerator engine). Preliminary results encouraged continued interest from Honeywell and combustor development is continuing toward full commercialization. Successful operation was displayed off-site during four separate rigorous test sessions, one at FETC in July 1998, two at Solar Turbines in October and December 1998, and one at Honeywell in February 2000. Although the combustor has yet to be tested in an actual engine, the project technical goals were achieved.

The most interesting results of this project included:

- Preheat in excess of 1000°F was applied during the tests. The combustors survived these elevated preheat temperatures and were actually able to operate at lower flame temperatures, resulting in lower NO<sub>x</sub> emissions. Increased preheat resulted in greater flame stability which ultimately reduced NO<sub>x</sub> emissions.
- Project goals regarding ignition and turndown were consistently met and demonstrated over a suitable range of operating pressures. Off speed stability was not addressed because the combustor was never run in an engine.
- NO<sub>x</sub> emissions of less than 2 ppm, comparable to or lower than existing steam injection and SCR control systems, were displayed in tests at Alzeta and Honeywell.



- Combustor pressure losses were consistently less than five percent of operating pressure.
- Lower life cycle costs resulted from a number of improvements made in the manufacturing techniques.
- In the majority of the tests, CO and hydrocarbon emissions were extremely low (less than 9 ppm).
- The combustors displayed good thermal shock resistance to tolerate instantaneous fuel cut off at full load.
- All of the designs were modular, and thus easily maintained both in Alzeta's manufacturing facility and in the field.

After carefully considering patent claims, Alzeta filed an U.S. patent application for the GTSB combustor on January 22, 1999.

**Conclusions:**

The GTSB has now been tested at the facilities of two major gas turbine manufacturers and full commercialization is imminent. Several facts became clear as a result of this project:

- Excellent emissions are attainable at reproducible operating conditions corresponding to actual turbine operating conditions.
- Outward-fired burners are the preferred configuration for the targeted engines.
- It is possible to successfully package an entire mixer/burner assembly within the space available in commercial gas turbine engines.
- The flow rate of premix through the burner surface (or firing rate) needs to be increased linearly as pressure is increased to maintain a nearly constant velocity through the burner surface.
- Increased levels of preheat typical of recuperated gas turbines, such as the Parallon 75, lead to increased flame stability at lower flame temperatures and thus result in lower NO<sub>x</sub> emissions.
- Any injection of cooling air into the primary combustion zone needs to be carefully controlled to minimize interaction with the burner surface. Such interaction can result in high emissions of CO and hydrocarbons.

**Project Status:**

The project results are being used by Alzeta to design and develop burners and combustor for industrial-scale engines under a follow on contract between Alzeta and the Energy Commission (Contract # 500-00-004).

## **EPAG Projects Completed in 2001**

### **Solid Oxide Fuel Cell/Micro Turbine Gen. Hybrid**

**Contract #:** 500-97-012 **Project #:** 7

**Contractor:** Edison Technology Solutions/Southern California Edison

**Subcontractors:** Siemens-Westinghouse : Northern Research Engineering Corporation :  
University of California, Irvine : Energy System Services Corp. : Paragon Consulting

**Project Amount:** \$2,000,000

**Match Amount:** \$14,900,000

**Contractor Project Manager:** John Leeper (626) 302-8936

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Completed

#### **Project Description:**

The purpose of this project was to prove the concept of integrating two dissimilar electricity producing distributed generation technologies into one generation unit. The integrated hybrid system design consists of a 200 kW pressurized solid oxide fuel cell (PSOFC) and 50 kW microturbine generator (MTG). As designed, the hybrid would deliver 220 to 230 kW because the MTG operates below its normal inlet temperature. Atmospheric emissions from fuel cells are very low because fuel cells convert fuel to electricity by an electrochemical process without combustion. MTGs typically have higher atmospheric emissions than a fuel cell. However, in this hybrid, the fuel is converted electrochemically in the fuel cell. The hot exhaust gases exiting the PSOFC are expanded through the MTG turbine, driving the turbine's compressor to pressurize the fuel cell. Remaining available energy, the fuel cell exhaust, is used to drive an electric generator to produce additional electric power. The increased power generation occurs with no increase in either fuel consumption or atmospheric emissions.

The project risk is high for three reasons. First, the Siemens Westinghouse SOFC has not operated in pressurized mode. Second, SOFC technologies are still in the development stage. Third, integration of a fuel cell a MTG has not been attempted before.

#### **This project supports the PIER Program objective of:**

- Improving the energy cost/value and improving environmental and public health costs/risk of California's electricity by providing reliable, diverse, energy-efficient, low-emission distributed electrical resources.

#### **Proposed Outcome:**

- To prove the concept of integrating two dissimilar electricity producing distributed generation technologies into one generation unit.

#### **Actual Outcomes:**

1. The PSOFC Factory Acceptance Test was successfully completed with 110 hours of operation at the Siemens-Westinghouse factory.
2. Installation of the hybrid at the University of California, Irvine was completed in May 2000. System startup occurred in June 2000. Proof of concept was achieved with sustained operation with the PSOFC supplying thermal energy to drive the MTG, including multiple system startups and shutdowns.
3. The Site Acceptance Test (SAT) was successfully completed in January 2001 after 100 hours of operation. The SAT was the principal part of the demonstration funded by PIER.

After over 150 hours of operation, overheating and failure of the PSOFC negative power lead occurred. Operation was suspended and the PSOFC was returned to the manufacturer for repair. A 50 kW MTG was not available, therefore, a 75 kW MTG was installed.

**Project Status:**

The proof of concept demonstration was successful. The Contractor will provide the report on the full test program, extending over 3,000 hours, in 2003 as a courtesy.

## **EPAG Projects Completed in 2000**

### **Advanced Fuel Cells (#165)**

**Contract #:** 100-98-003 **Project #:** 1

**Contractor:** Gas Research Institute

**Subcontractors:** Materials and Systems Research, Inc. : Inc. (MSRI) : Honeywell, Inc.

**Project Amount:** \$68,000

**Contractor Project Manager:** Ron Edelstein (847) 768-0889

**Commission Contract Manager:** Mike Batham P.E. (916) 654-4548

**Status:** Completed

#### **Project Description:**

The purpose of this project is to develop cost-effective, highly efficient fuel cell technology for distributed power generation from natural gas that has broad market applications in residential, commercial, industrial, and power generation. The project will capitalize on the results of previous GRI basic research that identified innovative cell designs and materials to reduce operating temperatures of solid oxide-fuel cells from 1000 ° C to 700 ° C. Those advances will enable large savings in the cost of the cells as well as the prospect of lower maintenance and longer life.

#### **This project supports the PIER Program objectives of:**

- Improving the environmental and public health costs/risk of California's electricity system because fuel cells emit low levels of atmospheric emissions and reduce the level of noise pollution vis-à-vis large scale power plants.
- Improving the energy cost and value of California electricity by providing high, fuel-to-electricity conversion efficiency.

#### **Proposed Outcomes:**

1. Provide the design of a low-cost, high-efficiency advanced fuel cell stack.
2. Provide fuel cell manufacturers with laboratory demonstrations of how to design and assemble solid oxide fuel cell stacks that operate below 700 ° C with very high efficiencies and power densities.
3. Develop fuel cell stacks that cost less than \$300 per kilowatt with electrical efficiencies greater than 50%.
4. Determine the best options for incorporating fuel processing within the stack, either through internal reforming or direct oxidation of methane.

#### **Actual Outcomes:**

1. MSRI has successfully tested a 250-Watt stack. A 100-Watt stack was operated 0.4 W/cm<sup>2</sup> for 500 hours with repeated thermal cycling and no voltage loss. The internally manifolded stack operated on hydrogen and natural gas.
2. Scale-up from 2"X2" to 4"X4" stacks is complete. Key stack design and metallic interconnect patents have been issued.

#### **Project Status:**

This project is complete. The Commission will fund additional research in this area in contract #500-00-022.

## Emerging Distributed Resource Technologies

**Contract #:** 100-98-001 **Project #:** 9

**Contractor:** Electric Power Research Institute (EPRI)

**Subcontractors:** Power Computing Systems : Proton Energy Systems, Inc. : Hpower : American Fuel Cell Corporation : NYSEG : International Fuel Cell : TMI : MSRI : Southern California Edison : Chugach Electric Assoc. : San Diego Gas and Electric Company : American Electric Power

**Project Amount:** \$428,650

**Match Amount:** \$7,097,973

**Contractor Project Manager:** Dan Rastler (650) 855-2521

**Commission Contract Manager:** Jairam Gopal (916) 654-4880

**Status:** Completed

### Project Description:

The purpose of this project is to promote the potential that distributed energy resources (DER) have to provide a substantial portion of the energy alternatives now demanded by California electricity users. Both energy service providers and customers need accurate and unbiased information on the benefits and liabilities associated with commercially available and emerging distributed resource technologies. DER technologies offer third-party energy service providers and energy customers innovative solutions to their energy service needs.

EPRI's Emerging DER Technologies target provides detailed information on commercially mature reciprocating engines and gas turbines, and emerging microturbines and fuel cell systems technologies. To gather this information, EPRI assesses advanced DER components, performs technology validations, and leads pre-commercial development on technologies that offer high pay-off. As a member, the Energy Commission will obtain intelligence in three distinct areas: rapid changes in technology, development of new distributed resources, and post-R&D commercialization initiatives. This target examines a balanced portfolio of near, intermediate, and long-term options.

### This project supports the PIER Program objectives of:

- Improving the reliability/quality of California's electricity by developing generation options that energy providers can utilize to provide unique solutions for peaking power issues, to enhance system reliability (system voltage control), and to assure power quality to their customers.
- Improving the energy cost/value of California's electricity by assisting in the development of innovative distributed resource technologies that can potentially provide lower delivered cost electricity than central station power.
- Improving the environmental and public health costs/risks of California's electricity by assisting in developing fuel cell systems and other environmentally preferred generation technologies to replace traditional central station power.

### Proposed Outcomes:

1. Provide unbiased accurate information on emerging DER technologies to increase customer choice and enable competition.
2. Provide information and assistance toward the resolution of cross cutting issues that generally slow the adoption process.
3. Bring to market readiness fuel cell technologies that include polymer electrolyte membrane (PEM) fuel cell systems and ultra-high efficient solid-oxide fuel cells (SOFC).

4. Accelerate the development of spark-ignited and micro-pilot, dual-fuel natural gas engines with major engine manufacturers for commercial applications in the 600 kW to 2 MW size range.
5. Conduct a Tailored Collaboration entitled “Workshop on Environmental Impacts of New Generation in California” to inform the public debate on the environmental effects of new generation options.
6. Conduct a Tailored Collaboration entitled “Emissions Testing and Certification Guidelines for DG Generators” to reduce the time and cost of DG technologies to meet existing and future emissions regulation.

**Actual Outcomes:**

1. Unbiased accurate information.
  - *Assessment of Distributed Resource Technologies* (TR-114180 ) was published.
  - Bench and field tests were conducted on PEM fuel cells and microturbines, and detailed technology assessments—including data on performance, emissions, and power quality characteristics—were published as *50 kW PEM Fuel Cell System Design, Fabrication, and Test: System Design—Final Report* (1000771).
  - A state-of-the-art assessment - *Assessment of Small Reciprocating Engine Manufacturers and Generator Set Packagers* (1000766) —was produced on internal combustion engines for electric generation applications.
  - A market study report—*Distributed Generation Market Study: Advanced Turbine System Program* (TR-112174) —was published on advanced turbines.
  - *Intelligence Reports*—quarterly reports on the latest breaking information on DER technologies—were published.
  - DER technologies were evaluated through site visits and meetings with leading manufacturers, and results were published in quarterly reports and technical reports.
  - An annual national DER conference was organized, providing a forum for utilities, energy companies, equipment manufacturers, and vendors to discuss the latest technology, market, and policy developments.
2. Resolution of cross-cutting issues.
  - A report—*Gas Turbine Recuperators: Benefits and Status* (TR-113745 ) —was published on the benefits and status of gas turbine recuperators.
  - A report—*Assessment of Emission Control Technologies for Distributed Resource Options* (TR-113743 ) —was published on emission control technologies for DR options.
  - The performance of a 7-MW gas turbine for transmission and distribution grid support and a residential fuel cell were evaluated.
3. Fuel cell technologies.
  - An advanced solid oxide fuel cell (SOFC) system was successfully tested. Test results were summarized in a report - *Demonstration of a High Efficiency Solid Oxide Fuel Cell-Microturbine Hybrid Power System: Interim Report: Factory Testing* (1000751).
  - A technology assessment of residential power systems—*Technology Assessment of Residential Power Systems for Distributed Generation* (TR-113897) - was published.
  - An assessment was published of fuel-processing technology for fuel cells—*Hydrocarbon Reformers for Fuel Cell Systems* (TR-113742).
  - A report evaluating 100-kW to 300-kW SOFC systems was published.
  - A bottom-up assessment of planar SOFC technologies was conducted, investigating the details of the cell, stack, subsystem, and balance-of-plant. A report—*Reduced-*



*Temperature, Anode-Supported, Planar Solid Oxide Fuel Cell Systems: Product Definition* (1000773) —summarized results.

- A report was published on factory test data and on market and economic analysis of 5-kW residential power generators.
  - A report—*50 kW PEM Fuel Cell System Design, Fabrication and Test: Utility/User Interface Issues* (1000750 ) —was published on an analysis of a 50-kW PEM system for commercial applications.
4. Natural gas engines.
    - A report —*Reciprocating Engines for Stationary Power Generation: Technology, Products, Players, and Business Issues* (TR-113894 ) —was published on reciprocating engines for stationary power generation.
  5. A workshop entitled “*Workshop on Environmental Impacts of New Generation in California*” was held in San Diego in October 1999, and a final report was published.
  6. The scoping study was completed and a report —*Emissions Testing and Certification Guidelines for Distributed Generators* (1007452) —was published.

**Project Status:**

The Commission’s participation in these targets ended December 31, 2000. The tailored collaboratives are complete.

## **Fuel Cell Development and Demo**

**Contract #:** 500-97-011 **Project #:** 2

**Contractor:** San Diego Gas and Electric Company

**Subcontractors:** M-C Power Corporation

**Project Amount:** \$300,000

**Contractor Project Manager:** Al Figueroa (619) 654-8614

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Completed

### **Project Description:**

The purpose of this project was to demonstrate the performance and reliability of a molten carbonate fuel cell (MCFC) electric generating technology with upgraded system components. Proving the efficiency and effectiveness of fuel cells helped propel this low-emission, electric generation technology into the marketplace. This project assisted in the advancement of MCFC technology by providing labor and selected materials for modifying the existing balance-of-plant (BOP) components designed for a 250 kW capacity MCFC demonstration plant at the Marine Corps Air Station Miramar. Balance-of-plant modifications were required to accept the next generation fuel cell stack having a capacity of 75 kW. An improved design of MCFC fuel cell stacks was tested and demonstrated at the Miramar plant. Other system components, including a new hot gas blower and turbo charger, were also tested. Additionally, an assessment of the technical feasibility of integrating micro-turbine generator technology with the MCFC technology was done.

### **This project supports the PIER Program objective of:**

- Improving the reliability/quality of California's electricity by offering energy efficient, low-emission alternate sources of electricity that diversify the State's electrical generation resources.

### **Proposed Outcomes:**

1. A modified BOP suitable to accept M-C Power's 75 kW MCFC stack.
2. Testing and evaluation of a new hot gas blower and turbocharger for a reliable performance.
3. Assessment of technical feasibility of integrating micro-turbine technology with the MCFC technology.

### **Actual Outcomes:**

1. The project resulted in a modified reliable BOP suitable for accepting the M-C Power's 75 kW MCFC stack.
2. New hot gas blower and turbocharger units were tested and evaluated. The new units were reliable during the BOP testing and subsequent 75 kW MCFC stack testing. The system operated continuously for nearly 3,000 hours.
3. Assessment has revealed very favorable prospects of integrating the micro-turbine technology with the MCFC technology.

### **Project Status:**

The project has been completed.

## **EPAG Projects Completed in 1999**

## **Analyses and Technology Transfer for Fuel Cells - National Fuel Cell Research Center**

**Contract #:** 500-98-052

**Contractor:** University of California, Irvine

**Subcontractors:** Southern California Edison : M-C Power Corporation : Siemens-Westinghouse : Energy System Services Corp.

**Contract Amount:** \$305,733

**Match Amount:** \$14,332

**Contractor Project Manager:** G. Scott Samuelsen (949) 824-1999

**Commission Contract Manager:** Arthur J. Soinski Ph.D. (916) 654-4674

**Status:** Completed

### **Project Description:**

The purpose of this Agreement was to improve the understanding of the operation of fuel cell and fuel cell/microturbine hybrid systems and to improve technology transfer capabilities at the National Fuel Cell Research Center (NFCRC). To do improve our understanding of these two electricity generating systems, the NFCRC would develop new computer modeling tools. To address technology transfer the NFCRC would:

- Design, construct and operate a multi-function room on the University of California, Irvine (UCI) campus.
- Establish the Educational Facility for Ambient Air Monitoring on the UCI consisting of air quality monitoring instrumentation and computers for data collection and presentation.
- Establish a web site to make the information developed as a part of this project available to the wider public.

### **This project supports the PIER Program objective of:**

- Improving the reliability/quality of California's electricity by helping advance the development of clean and energy efficient distributed power generation technologies which will provide enhanced system reliability, highly efficient power generation, cleaner environment, and reduced cost.

### **Project Outcomes:**

1. A review was made of existing models. Characteristics of those models were summarized, and advantages of the project's modeling methods and approach were described. These models can be used to design of fuel cell system components, to design fuel cell testing procedures, and to better understand fuel cell systems and microturbine operation and performance.
2. Computer simulation models for three fuel cell and fuel cell/microturbine components were developed:
  - A tubular solid oxide fuel.
  - A reformer that converts hydrocarbon fuels into a hydrogen-containing gas mixture to be used by the fuel cell.
  - A microturbine.
3. The technology transfer accommodations, ambient air monitoring workstation and website have been completed and are in routine use.

### **Project Status:**

The computer modeling approaches used in this project are being applied to other fuel cell and fuel cell/microturbine systems in a subsequent Interagency Agreement (Contract #500-99-028).

### **Micro Turbine Generator (Distributed Generation)**

**Contract #:** 500-97-012 **Project #:** 8

**Contractor:** Edison Technology Solutions/Southern California Edison

**Subcontractors:** University of California, Irvine : Energy System Services Corp. : CAMS : Paragon Consulting : Capstone Turbine Corporation : Bowman Turbines, Inc.

**Project Amount:** \$500,000

**Match Amount:** \$1,500,000

**Contractor Project Manager:** John Leeper (626) 302-8936

**Commission Contract Manager:** Avtar Bining Ph.D. (916) 657-2002

**Status:** Completed

#### **Project Description:**

The purpose of this project was to test small gas turbines in distributed electrical generation applications. This project is part of a public/private sector \$2 million collaborative microturbine generator (MTG) transition procurement and testing project at the University of California, Irvine (UCI).

This project procured and tested small gas turbine technology in distributed generation applications. The MTG, which is typically rated in the 30-100 kW range, is a small combustion turbine that has an integral high-speed generator.

#### **This project supports the PIER Program objectives of:**

- Improving the reliability/quality and the energy cost/value of California's electricity by offering alternatives for distributed generation applications that will reduce the costs of transmitting and distributing electricity.
- Improving environmental and public health costs/risk of California's electricity by reducing NO<sub>x</sub> emissions from on-site electrical generation.
- Impacting local and state economy by contributing information to help in developing an emerging distributed generation technology industry in California.

#### **Proposed Outcomes:**

1. Enhance system reliability - MTGs can enhance system reliability benefits when operated as distributed generators.
2. Reduce NO<sub>x</sub> emissions.
3. Economic Development – Procure MTGs from two California-based MTG manufacturers. If successful, this project will contribute information to help in developing an emerging distributed generation technology industry in California.

#### **Actual Outcomes:**

1. Two Bowman (35 kW and 60 kW) and a Capstone 28 kW were tested. The Bowman 35 kW operated for 100.6 hours, the Bowman 60 kW operated for 4.2 hours and the Capstone 28 kW operated for 1,879 hours. Both Bowman units operated on a sporadic basis due to component failures and operational restrictions imposed by unacceptably high noise levels. The Capstone microturbine operated within the manufacturer's claimed efficiency rating at full load.
2. Both the Bowman 60 kW and the Capstone 28 kW units emissions test showed NO<sub>x</sub> and CO levels that met or were well below limits set by the South Coast Air Quality Management District.
3. The Capstone 28 kW unit's power quality measurements met the Institute of Electronics Engineering's standard for harmonic control in electric power systems.

#### **Project Status:**

The project has been completed.